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REDUCTION OF FUEL USE

IN

GRAIN DRYING

Report No. 88-5500 November, 1988

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IN

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Report No. 88-5500 November, 1988

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At the same time that this review of grain drying research was initiated, Marcel Levesque started a similar review for Agriculture Canada. After discussions with Mr. E. Brubaker, Manager of the Agricultural Energy Centre, it was decided to combine the effort. Therefore, it was agreed that Marcel Levesque would supply the information and draft manuscript dealing with current drying systems (Chapter 1), while Lambert Otten would review the other areas and prepare the report.

The report was to be submitted to the Ontario Ministry of Agriculture and Food and the Ministry of Energy for approval. Upon acceptance, copies of the report were to be distributed to the Engineering and Statistical Research Institute, Agriculture Canada.

We wish to thank Mr. E. Brubaker for allowing us to work with Agriculture Canada in preparing this report and for reviewing a number of chapters before his retirement in April, 1987.

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REDUCTION OF FUEL USE IN GRAIN DRYING

EXECUTIVE SUMMARY

A. INTRODUCTION

The main reason for the review of the grain drying research was the development of a list of research priorities based in part on a cost/benefit analysis. A secondary objective was the presentation of information useful to researchers, extension personnel and scientific authorities involved in research funding. Although the material presented in this report has fulfilled the secondary objective, very little information was found to address the primary one from a cost/benefit analysis point of view.

It appears that grain drying research can be classified into four distinct groups; namely,

(i) theoretical and empirical research aimed at understanding and prediction the drying process (hybrid characteristics, model development, grain quality);

(ii) research dealing with the development of new drying technologies; (microwave, desiccant, solid-solid contact, spouted bed, use of preservatives);

(iii) research to modify existing equipment and processes to improve energy efficiency and grain quality (recycling, heat exchangers, heat pumps, automatic control systems, temperature staging, tempering, dryeration, stirring equipment, corn cribs); and

(iv) use of renewable energy sources instead of fossil fuels (solar, biomass).

All most all of the above mentioned research topics are either at a preliminary stage in which cost analysis is not yet a factor or they are of

no commercial value even though they are of importance to the end user. For example, the determination of required airflow rates for low-temperature drying under (LTD) various conditions at different geographic locations is necessary to reduce the risk of spoilage but the information has no commercial value. Nevertheless, if the availability of such data induced more farmers to use LTD, they will probably use less energy to dry their crop and produce a better product.

Even in cases where research has resulted in a commercial product, the cost/benefit information is often subjective. For example, the recent introduction of an automatic control system for high-temperature crossflow dryers has not provided reliable data as to the success in reducing energy consumption and labour requirements, and in improving grain quality. Therefore, it would be difficult to predict what the impact of control systems for other types of dryers will be. It may well be that automatic controls may result in less management time but will not reduce the operating costs to warrant the capital investment.

In each of the review chapters the topic is introduced with a brief description of the process or equipment, followed by the information obtained from the literature review. Each major topic is then closed with a summary and a list of references. This particular approach was selected so that each topic would be complete in itself. Over 500 references were used in preparing this review.

B. ASSESSMENT OF TECHNOLOGIES

The following assessment of grain drying systems and processes follows the sequence in which they are presented in the report. Where applicable, the commercial potential, probable development costs and identification of

manufacturer involvement will be considered.

Identification of manufacturer involvement is obviously difficult because the grain industry is currently and probably for the near future in the most depressed state in decades. Furthermore fuel prices are much lower than had been anticipated a few years ago.

CURRENT DRYING SYSTEMS

1. Low-Temperature Drying

Extensive research in the seventies has shown that low-temperature drying (LTD) results in a high quality product and that it has a potential for energy savings of about 20% (although some U.S. researchers claimed savings up to 50% for their climatic conditions). For most of Ontario the limiting factors for LTD are that the initial moisture content must be less than 24%, the airflow rate greater than 26 L/(s.m^3 of grain) and the grain depth less than 4.5 m. The technique has been accepted by farmers and there is a growing interest in its use, especially as more faster maturing hybrids become available.

Since the success of LTD is dependent upon the prevailing weather conditions at each geographic location, minimum airflow data and operating guidelines should be available for different regions. At present complete guidelines have been published for drying of cereal grain and corn in Manitoba and partial guidelines for corn drying at a few Ontario locations. Appropriate modelling software is available so that only simulation studies using stochastic weather data need to be performed for the remaining locations of interest. The cost to provide a complete set of guidelines for drying cereal grain and corn in Ontario is estimated to be less than $50,000.

Development of an automatic control system for low-temperature drying is necessary to optimize energy use while preventing spoilage. It appears that the software for full-bin drying is available; however, changes are required to account for layered filling and other variations in operating procedures (including the use of stirring equipment). The development of more suitable humidity sensors would also be beneficial.

Work in the area of corn cribs deserves additional attention. Automatic loading and unloading of cribs is the key to further interest in cribs. It is, however, unlikely that the volume of corn harvested as cob corn will significantly increase in Ontario so that commercial interest in the development of new systems is not expected at this time.

Solar-assisted LTD has proven to be not economical under Ontario harvest conditions. In fact maintenance costs would appear to be much higher than anticipated in earlier research. Many of the collector materials, which were supposed to have a life expectancy of ten years, need to be replaced after only five years of operation. There is little incentive to continue research in the use of solar energy in conjunction with grain drying in Ontario. It would, however, be useful to evaluate the success of the various solar drying and heating projects funded by the government during the past decade. This would provide valuable information for future projects when solar energy becomes again popular or becomes cost competitive as an alternate energy source for agriculture.

2. <u>High-Temperature Drying</u>

There are a number of different high-temperature dryer designs in use. They are commonly classified according to the relative direction of airflow and grain flow so that one has crossflow, concurrent-flow, countercurrent-

flow and mixed-flow dryers. In addition, there are batch-in-bin dryers, simple batch dryers and recirculating batch dryers.

A considerable amount of experimental research has been done to study the effect of airflow rate and drying temperature on energy efficiency, dryer capacity and grain quality for all types of high-temperature dryers. Similarly, mathematical models have been developed to simulate the drying process in those dryers.

For crossflow dryers it has been shown that at a fixed drying temperature the energy consumption increased with increasing airflow rate, while moisture content differences across the column decreased. On the other hand at a fixed airflow rate, the energy consumption decreased with an increase in drying air temperature, while the moisture differential increased. Similar observations have also been made for mixed-flow dryers.

Concurrent-flow dryers allow the use of much higher air temperatures than crossflow dryers because the hottest air comes in contact with the wettest grain. As a result the energy efficiency of concurrent-flow dryers is 20 to 25% higher while the grain quality is better, especially when countercurrent-flow cooling is used. Simulation and experimental studies have shown that concurrent-flow dryers are most efficient at high drying temperatures and low airflow rates. Multi-stage concurrent-flow dryers have been developed with tempering zones between each drying stage. Although staging allows recycling of the exhaust from one stage to another, the effect on efficiency is minimal as compared with single stage units.

Countercurrent-flow dryers are modified batch-in-bin systems in which grain is loaded from the top and unloaded continuously at the floor level with a sweep auger. These units provide considerable flexibility in operating conditions and because of the deep bed (1 to 2m) the energy

efficiency is higher than for most other dryers. Cooling of the grain is normally done in storage bins.

Various design modification have been made to the different high-temperature dryer configurations with the objective of improving energy efficiency and grain quality. These include use of temperature staging, reversing the airflow or installing grain inverters at different levels in crossflow dryers, allowing grain to temper before cooling or at various drying stages. Most of these innovations have been successful and most commercial dryers are manufactured with the innovations as part of the basic design or as options.

Other attempts at improving dryer efficiency include use of heat recovery systems and alternate energy sources. Some of these modifications have been successfully applied, others are economically not feasible.

The most recent work on high-temperature dryers deals with the development of automatic control systems. This work is aimed at improving energy efficiency and grain quality by reducing overdrying and at decreasing labour costs. Although some microcomputer and microprocessor-based control systems have been marketed, little scientific information is available on whether or not they meet the various objectives. Reliable data on cost effectiveness are also not yet available.

The area of microelectronics will play a major role in optimizing grain drying processes: however, success of introducing control systems will greatly depend on the capital cost because grain drying is basically a short term operation. It seems that systems based on costly hardware, such as moisture content sensors, will only be of interest to high volume commercial operations. In contrast farm applications must be low cost and will

therefore require more sophisticated drying models which do not depend upon expensive senors.

The four areas of future research related to control system development are modeling of the drying process, development of optimum control strategies, grain quality criteria, and sensors development. Modeling of the drying process covers a wide area of applications because it depends on the equipment and method used and the drying and grain conditions. Although many models have been developed, more work is needed to include grain quality criteria and control strategies. The development of less expensive and more reliable humidity and moisture content sensors is also a major need. Ideally one would also like to have sensors which monitor changes in grain quality during the drying process.

Further research is also needed to develop new high-temperature drying processes and equipment designs. These may involve completely new concepts or may combine the optimum features of current designs (hybrid dryers). Use of insulation to reduce heat loss from large commercial dryers has not been considered sufficiently, although some units are available with insulated plenums.

NOVEL DRYING SYSTEMS

1. Microwave Drying

Use of microwaves to dry grain is technically feasible and has shown to be more energy efficient than conventional high-temperature drying while producing a similar or higher quality product. The first attempts at producing commercial microwave grain dryers have met with limited success, probably because of insufficient data on the design parameters and operating conditions. Some research is in progress in the U.S. to alleviate this

problem; however, economic constraints will likely restrict the use of microwaves to drying and processing of special crops rather than feed grains. At present there are no companies in Ontario working on the development of a commercial microwave grain dryer. Research in the use of microwaves for grain drying should be continued.

In some countries microwaves have been used to destroy bacteria in foods. Some work has also been done to treat peanuts infected with toxin producing moulds. If it can be shown that microwaves destroy the moulds or modify the toxins the interest in developing microwave equipment for the agricultural industry is assured. A review of the research dealing with the effect of microwaves on micro-organisms is recommended.

2. Desiccant Drying

Desiccant drying of grain involving use of dehumidified air is similar to low-temperature drying and offers no significant advantages for Ontario conditions. Similarly, drying of grain using a method of mixing a desiccant with wet grain appears to be less attractive than low-temperature drying.

Neither technique has been evaluated on a commercial scale so that no reliable data have been found to determine the capital and operating costs. Furthermore, unless extensive and efficient use of solar energy is possible, the energy consumption appears to be equivalent to conventional high-temperature drying.

Application of desiccant drying techniques to special grain crops, such as seed corn, is a possibility; however, more work is required to determine the drying kinetics and design data.

3. Solid-Solid Contact Drying

Research has shown that particulate medium drying of grain and oilseeds is feasible. The drying efficiencies reported in the literature are higher

than those of high-temperature dryers; however, much of the information was obtained using small-scale systems and often involved removal of only a few percentage points of moisture. More reliable energy and costs data are expected with the development of prototype units.

Aside from the potential of high drying efficiencies, solid-solid contact dryers are expected to allow accurate control of the final moisture content of the products as small amounts of moisture are removed during each pass through the dryer. It is also possible to control the drying rate at different points in the process so that the product quality can be maintained.

Another advantage of solid-solid drying is the potential to control insect problems. In most high-temperature and all low-temperature processes some of the grain bulk does not reach sufficiently high temperatures to destroy all the insects and micro-organisms. In contrast, the intimate contact between the hot drying medium and the grain bulk essentially ensures that all the insects and micro-organisms are destroyed, especially as the drying medium is much hotter than the air in air-drying.

As mentioned in the review, one manufacturer is building a prototype of a commercial unit. Although the design of the unit was the results of a decade of research, there seems to be sufficient scope in sold-solid contact drying to continue the research in an attempt to develop different dryers and to discover better heat transfer materials.

4. Fluidized And Spouted Bed Drying

Fluidized bed drying is not feasible for large cereal grains or corn but may be of interest for drying and treatment of small oilseeds.

Spouted bed drying is not only possible but has been used successfully

in a few commercial applications. As in the case of solid-solid dryers, spouted bed dryers allow accurate control of grain moisture and quality. It is, therefore, expected that spouted bed dryers may become important in processing grains for the export markets. However, a great deal of fundamental and applied research is needed to develop the technology before it is suitable for widespread applications in the agricultural sector. Much of this work will be in the developement of modified spouted beds.

5. Use Of Preservatives In Low-Temperature Drying

Although the addition of preservatives to grain allows an extension of the drying period in low-temperature drying, it is probably more advantageous to shorten the drying time by increasing the airflow rate, add more heat or use a layer-filling method. On the other hand, if toxins in feed corn continues to be a major concern, the addition of preservatives may well be the solution. For this reason alone it is recommended that work on preservatives in low-temperature drying be continued. This research should include an investigation of different chemicals, the development of new application techniques, and extensive field trails.

HEAT RECOVERY SYSTEMS

1. Recycling Of Cooling Air And Exhaust

Recycling of cooling air and unsaturated exhaust has resulted in significant energy savings in all applications. It is the most effective and economical way of recovering energy in high-temperature drying of grain with continuous-flow dryers. It has therefore become a standard feature in all new dryers.

Although little further research is needed on recycling of cooling air, transfer of information to the farmer could be improved. A factsheet or a

manual describing various retrofit designs would be beneficial. Any research in this area should address recycling of unsaturated exhaust in an effect to optimize energy use. The present rule of thumb is to recycle the exhaust from the lower 25% of the drying column in a crossflow dryer but the actual amount depends on dryer design and operating conditions.

2. Heat Exchangers

Recovery of heat from the saturated exhaust of high-temperature dryers with a heat exchanger has been successful; however, most installations included recycling of cooling and unsaturated exhaust as well. Therefore some of the reported savings were due to recycling rather than the exchanger. The incremental savings attributed to the exchanger appear to be insufficient to make exchangers economically attractive at this time.

It must, however, be remembered that the researchers were more interested in looking at the technical feasibility than at the economic one. In some instances costly commercial exchangers were purchased and there is considerable room for innovations in design and material selection. Many of the criteria of exchanger design for industrial use do not apply to the farm application. In many cases the exchanger can be very simple and be constructed from inexpensive materials, such as used roofing steel.

Some useful information on the design and use of such systems is available and should be published for distribution to the farm community. It also recommended that heat exchanger work be continued with emphasis on developing simple designs and testing inexpensive materials.

A secondary benefit of heat exchangers is a reduction in emissions from the dryer. The wet environment in the exchanger causes the particulate, especially the 'red dog', to settle out. While emissions are not a concern to most farmers, it is a problem with commercial elevators located near

residential areas.

3. Heat Pump Drying

The applicaiton of heat pumps to grain drying using either a closed-loop or open-loop appears technically feasible, although care must be taken with the design of the system to avoid frosting problems. It has also been shown that the specific energy consumption in heat pump LTD systems is significantly lower than with resistance heaters. The same appears to be true for HTD dryers but at a major reduction in drying capacity.

The main problem with heat pump drying is the large capital cost. It has, therefore, been suggested that the heat pump should also be used for heating purposes when it is not used for grain drying.

At the moment too few studies have been performed to provide specific recommendations and a great deal more R & D work is needed.

ALTERNATE ENERGY SOURCES

1. Solar Energy

Research has demonstrated that solar energy is generally not suitable for high-speed, high-temperature drying; however, it may be used effectively in low-temperature drying. Solar-assisted LTD research has resulted in a large number of collector designs, experimental and theoretical feasibility studies, and the development of mathematical models. Due to the geographic variations in availability of solar energy and prevailing weather conditions, most studies have been repeated in all grain producing provinces in Canada and states in the U.S.

As far as Ontario is concerned, drying of corn with solar energy as a supplemental heat source is technically feasible but economically not justifiable. The same conclusions has been drawn by most researchers in

North America. Solar systems must therefore have multiple applications rather than just grain drying.

Further work is required to obtain information on the potential of spoilage with solar-supplemental, low-temperature drying systems. There is also a need to determine the long term maintenance and operating expenses of integrated solar systems. Much of the current economic data are based on assumed life expectancies of the various components rather than experimental observations.

2. Biomass To Dry Crops

Biomass in the form of crop residues, such as straw, stover and cobs, has the potential of becoming a significant source of energy for crop drying and space heating in Ontario. Although there are conflicting reports regarding the present economic feasibility of utilizing biomass-fueled systems, multi-use of the equipment and/or increased fuel costs could change this in the future.

Integration of residue collection and handling into general agricultural practices is needed for optimal design and use of equipment, and management of the crop production process. Better equipment is required to ensure timely harvesting and processing of the residues without interfering with the normal harvest operation. Research must be aimed at the development of multi-use equipment capable of handling various crops and residues to maximize equipment use and to reduce capital and operating costs. Similarly, additional work is needed to develop appropriate residue storage facilities and processing equipment. In the latter case packaging of the residue for easier storage and handling is a major component.

A considerable amount R&D work has been done to develop furnaces to

burn crop residues. Simple straw-fired furnaces have been available commercially in Europe for at least two decades, and some of these units have been imported for space heating. A number of those furnaces can also be used to burn stover and cobs. Research has also demonstrated that two-stage gasifiers provide a more efficient combustion process than simple furnaces. Further work in this area is needed before optimum designs are expected.

Almost all of the experimental effort has dealt with individual components of the energy-from-biomass system. Additional experimental input is required to develop an integrated system with automatic controls. For example, automatic feeding of various biomass materials to the furnace is an area which has not received sufficient attention.

The environmental impact of emissions from furnaces must also be considered; especially if the products of combustion are used directly to dry grain. Deposition of carcinogenic compounds onto grain requires more study.

There is also insufficient experimental data on the long term effect of residue removal on the soil ecosystem. The impact of residue harvest on organic matter content, nutrient balance, water holding capacity, soil tilth, weed and pest related problems, bacterial activity, erosion potential, and primary crop yield and quality must be considered over the long term.

There appears to be a need to expand the thermophysical properties data base of biomass materials. To date most researchers have used the results of a limited number of studies while accurate and complete data are essential to the design of the system.

In contrast to the situation in the U.S., where a number of grain dryer

manufacturers are developing biomass systems, there has been little industrial interest in Ontario. At present only Moorehouse of Florence and Newmac Mfg. Inc. of Woodstock have worked on the development of economical crop residue furnaces. Moorehouse is of the opinion that under the current economic conditions in agriculture further investment by his company in R&D is not warranted. On the other hand, Newmac Mfg. Inc. expects to start marketing 300 MJ/h furnaces for space heating in 1988; grain drying would require furnaces three time the size.

GRAIN CHARACTERISTICS

Although the data base relating drying rate to hybrid characteristics is still limited, the difference in drying rates is of the same order as the energy savings resulting from various innovative equipment and process changes. Therefore, this type of investigation is of equal importance and may lead to the development of fast drying hybrids or a process to enhance drying by altering the properties mechanically.

Since the effect of hybrid properties on artificial drying has received little attention and is, therefore, not well defined, additional research must be done.

C. RESEARCH PRIORITIES

In order to obtain some ranking of R&D priorities, the following table was prepared. It is based on both quantitive and qualitive information obtained from the literature as well as the author's experiences in grain drying research during the past decade. The capital and operating cost columns for both LTD and HTD are based on a comparison with the system without the indicated modifications, while for the novel drying systems the entries are with respect to a conventional high-temperature crossflow dryer.

The energy savings column uses conventional HTD as a reference while energy savings resulting from modification to the LTD system are with respect to basic LTD.

It is clear from the table that almost all modifications and new drying systems will have a higher capital cost than the current ones. Similarly, the operating costs other than energy use are also expected to be higher in most cases. Therefore, it is essential that modified and new systems result in significant energy savings before they become economically attractive. A major difficulty in correlating costs and energy savings is that the use of a grain system may vary greatly from one site to another; thus, the yearly drying volume becomes an important variable.

The R&D priorities ratings found in the last column of the summary table were based on the economic feasibility statements of various researchers, expected level of convenience to the end user, the effect on grain quality, and the potential of manufacturer involvement.

The LTD Airflow Information topic was given the highest priority rating because the potential benefit to farmers is considered to be high while the cost and effort to obtain the data is low in comparison with all other drying research. Distribution of the information could be done through the OMAF extension services.

The development of expert control systems for low-and high-temperature drying is considered to be the second highest priority. Low-temperature drying, including natural drying, is a long term process in which the conditions are constantly changing. Only automatic control based on ambient temperature and humidity measurements will ensure optimum use of energy while maintaining grain quality. Use of stochastic weather data would assist in

predicting the amount of drying that can be expected during the fall and/or spring given the starting data and initial moisture content.

Automatic control of the high-temperature drying process is considered by most grain drying experts to be the most significant recent development in drying of agricultural products. In addition to energy and labour savings, microelectronic control systems have the potential to ensure high product quality. A major component of the research thrusts in this area should be the development of affordable and reliable sensors to measure humidity, grain moisture content and grain quality.

Heat recovery using air recycling and/or heat exchangers was given the third highest priority because both have been shown to be economically feasible by some researchers. As mentioned above, recycling research should address the question of how much of the unsaturated exhaust should be recovered and how can this be done economically. Heat exchanger research should be aimed at producing innovative designs and at evaluating the performance of inexpensive materials.

Redesign of continuous-flow, high-temperature dryers to integrate such concepts as temperature staging, tempering and cyclic drying, etc. was also given a rating of three. Some of these concepts are already used in some commercial dryer but others are not yet used. In other instances the techniques are used but not in an optimum manner. It is expected that some basic modeling work is necessary as well as field testing of the concepts. Since introduction of these and other concepts are often related to particular types of dryers, manufacturer cooperation can be expected.

Research in the efficient use of biomass in the form of crop residues is highly recommended. Although the scope of the work involves ecological, environmental and engineering aspects, the development of integrated systems

compatible with modern agricultural practices is particularly urgent if crop residues are to have a significant impact in the next decade.

Further investigations into the relationship between artificial drying rates and hybrid characteristics is of fundamental interest. Not only may this research lead to a better understanding of the drying process itself, but it may also lead to the development of faster drying hybrids. This topic has been given the same rating as biomass research because it is expected to be a long term effort.

Microwave, solid-solid and spouted bed drying were rated fifth in the priority listing. All three methods have the potential of providing significant energy savings and of allowing accurate control of the grain quality; however, further development of suitable equipment seems necessary to keep the capital and operating costs sufficiently low. The amount and cost of the research is expected to be substantially higher than in the first four sets of research topics.

Both solar-assisted and use of preservatives in low-temperature drying and the use of corn cribs were given the same priority rating because none of these offer much of an advantage over the basic low-temperature drying technique as far as Ontario is concerned. There may, however, be some specific applications where further research is warranted. For example, the use of preservatives may be another tool in combating mycotoxcins in grain corn.

The large capital cost of installing heat pumps in both LTD and HTD systems essentially eliminates them for use in grain drying alone. Therefore, this topic has been rated the second lowest in list. There have been suggestions that multiple use of heat pumps would change the economic

feasibility but in reality it is difficult to size heat pumps for different applications.

The use of desiccants in drying of grain corn and other large volume grain crops is not expected to be competitive with low-temperature drying. The cost of desiccants, regeneration and other equipment is too high. There may be a case made for desiccant drying of other crops and seed grain but further research is needed to verify this. As far as corn drying is concerned the topic is of a low priority.

Solar-assisted, high-temperature drying of grain corn is economically not feasible because the cost of collectors is simply prohibitive for most Ontario conditions.

Finally, it is recommended that truly innovative drying processes or equipment should be considered on their own merit and should be given a high priority for funding.

INFORMATION SUMMARY AND RESEARCH PRIORITY LISTING

	REVIEW SECTION	CAPITAL COST	OPERATING COST(%)*	ENERGY SAVINGS(%)	GRAIN QUALITY	MANUF. INVOLV.	CONVEN-IENCE	ECONOMIC FEASIBILITY	PRIORITY
LOW-TEMPERATURE	1.2	-	-	<50	E	-	V.G.	YES	-
- AIRFLOW DATA	1.2	-	-	+15	E	NO	V.G.	YES	1
- CONTROLS	1.2	H	-	+15	E	?	V.G.	?	2
- SOLAR	4.2	H	+6 to 20	+25	E	NO	G	NO	6
- PRESERVATIVES	2.6	L	+10	?	G	NO	G	?	6
- HEAT PUMP	3.4	V.H.	?	+30	E	?	G	NO	7
HIGH-TEMPERATURE									
- CONTROLS	1.3	H	-	15	G	YES	G	?	2
- RECYCLING	3.2	L	-	10 to 40	G	YES	G	YES	3
- EXCHANGERS	3.3	H	-	5 to 30	G	YES	G	?	3
- HEAT PUMP	3.4	V.H.	?	10 to 60	G	YES	G	NO	7
- SOLAR	4.2	V.H.	?	20	G	NO	G	NO	8
- STAGING/TEMPERING	1.3	?	-	20	G	YES	G	YES	3
- BIOMASS		H	-50	-	G	YES	F	?	4
CORN CRIBS	1.2	?	?	<100	F to G	?	P	YES	6
- MICROWAVE	2.2	H	?	<50	G	?	G	?	5
- DESICCANT	2.3	H	+60	<50	E	NO	P	NO	7
- SOLID-SOLID	2.4	H	?	<50	G	YES	G	?	5
- SPOUTED BED	2.5	H	?	<30	G	NO	G	?	5
- HYBRID EFFECT	2.6	-	-	+20	-	NO	-	-	4

* Other than energy

Symbols: E - excellent
F - fair
G - good
H - high
V.G. - very good
V.H. - very high
P - poor

1.0 CURRENT DRYING SYSTEMS

1.1 INTRODUCTION

This section describes the most popular grain drying systems currently used in Canada. They include low-temperature and high-temperature dryers, combination drying systems, and dryeration. Also included is an overview of the state of research on those different drying systems. The predominant aim of the review is to present the use and management of the systems and to identify current research and development needs.

1.2 LOW-TEMPERATURE DRYING SYSTEMS

The term low-temperature drying (LTD) refers to drying of grain using either ambient air or slightly heated air. The main advantages of LTD systems are the preservation of quality, potential energy savings, flexible harvest schedule and lower investment cost. LTD systems exist where the grain is either dried on the cob, in the case of corn, or as shelled grain. In each case the air may either be forced mechanically through the grain or by natural wind effect.

The most popular LTD systems used on the farm consist of circular steel bins equipped with a perforated floor through which air is forced into the mass of shelled grain using an electric fan. Low-temperature drying may be further classified according to the filling schedule. In the case of full bin systems, the bin is filled in one operation and the fan is usually started after filling. In the case of layer filling, the fan is started immediately after the first layer of grain has been placed in the bin. A second layer is usually not added until the drying front has reached the top of the first layer.

The second most popular LTD system for corn consists of naturally

drying the husked ears in a crib. Systems also exist where ear corn is dried using forced air (Columbus and Van Hooren, 1985). Research has been carried out to determine the feasibility of using thin perforated columns similar to cribs for the drying of shelled grain without using forced air (Ferland et al., 1986).

In the case where heat is used for forced air systems, it is to reduce the relative humidity of the air only to the equilibirum relative humidity of the grain at the desired final moisture content. Typically the air temperature would be increased by 2 to 5°C.

The two principal sources of heat for low-temperature drying are solar and electric heat but heat pumps have been considered as well. Propane and natural gas are not applicable for LTD because the moisture released by the combustion is enough to maintain a high relative humidity at the low drying temperature (MacDonald et al., 1986).

Based on the Farm Energy Use Survey performed by Statistics Canada in 1981, the percentage of the principal energy source for drying wheat and corn are presented in Figure 1.1. The electrical and forced-air systems mainly represent LTD systems. Drying wheat is generally done using low-temperature systems while corn is mainly dried with high-temperature systems because of the higher harvest moisture content (Statistics Canada, 1981). However, low-temperature or ambient drying of shelled corn has become increasingly popular in Ontario, especially in south-western Ontario.

1.2.1 IN-BIN SYSTEMS

Much work has been done on low-temperature drying since the energy crisis of 1973. The earlier work was devoted to developing guidelines on the various operating parameters such as airflow rate requirements based on

harvest moisture content for different types of grain and the weather conditions at specific locations. Most of the design guidelines were developed initially based on continuous fan operations. The present standards for minimum airflow requirements of LTD bins are based on a 90% probability of successfully drying grain with a specified initial moisture content without spoilage (Morrison and Shove, 1986). The most recent work has put the emphasis on energy conservation by developing and testing various management strategies.

Pfost et al. (1977) used a computer simulation to evaluate and compare the performance of six different fan management systems with the practice of filling the bin all at once and operating the fan continuously. They found that clock control reduced energy consumption by about 50% but increased dry matter loss by 50% while humidistat control reduced energy requirements by about 40%, provided more drying and about the same dry matter loss as the continuous operation. They also compared single and sequential filling schedules. Their results indicated that sequential filling reduced energy requirements slightly, had little effect on drying rate but did reduce dry matter loss significantly under the weather conditions tested.

The effect of initial moisture content and harvest date on minimum airflow rate requirements for ambient drying using continuous fan operation was studied by Fraser and Muir (1981). Computer simulations were used to determine the rate of airflow required to dry wheat at Edmonton, Swift Current and Winnipeg and to dry corn at Winnipeg and London, Ontario. It was found that the airflow requirements decreased by approximately 50% for each month's delay in harvest and approximately doubled for each increase of two percentage points in initial moisture content.

Morey et al. (1979) also compared various management strategies using computer simulations. They found that continuous fan operation, under an appropriate fall shut-off and spring start-up procedure, was preferable to management strategies which involved turning off the fan based on relative humidity and temperature values, or a time clock. It was also found that filling the bin over a period of time allowed an increase in initial moisture content of up to 3 percentage points compared to a single-fill procedure.

The effect of weather, harvest date, initial moisture content and spring starting date have been studied by Mittal and Otten (1980, 1982) by modelling low-temperature corn drying using hourly weather records from 1965 to 1978 for Toronto and London, Ontario. They found that an airflow rate of 35.8 $L/(s \cdot m^3$ of grain) was suitable for about 86% of the years in London and 95% in Toronto; energy was saved by delaying the harvest date from October 1 to November 1; corn with an initial moisture content of 22% can be dried safely in any year; and, delaying the spring starting date from April 1 to April 15 resulted in reducing the fan-hours for all years. Using the same data, Mittal and Otten (1981a) evaluated twelve different fans and heater management schemes by computer simulation. They found that during favorable weather, continuous fan operation without supplemental heat was sufficient to dry corn, while additional heat was necessary during poor weather; and, with better fan and heater management an airflow rate of between 29.4 and 32.6 $L/(s \cdot m^3)$ was sufficient to dry corn from 24 to 15% moisture content in Southern Ontario in any year. However, none of the management schemes was found to be energy efficient as compared with high-temperature drying.

Morey et al. (1981) found by computer simulation of wheat drying that operating the fan with humidistat control after the drying front reached the

top of the bin, or shutting off the fan after September 15 when the drying front reached the top of the bin and completing drying in the spring, resulted in a reduction in energy use with grain deterioration comparable to continuous fan operation. They indicated that dry-matter decomposition levels decreased rapidly below 19% moisture content.

Data collected by Shove (1981) on low-temperature corn drying indicated that energy was more efficiently used if applied to supplying air rather than increasing the temperature of the drying air. It was also found that energy can be conserved by providing sufficient air to complete drying as early as possible to take advantage of favorable drying weather.

Sharp (1982) reviewed the literature on the application of simulation models to the study of the management of filling, fan control and the use of supplemental heat and stirring devices. He reported that Morey and Peart (1971) found that the optimum depth was significantly greater and fan power significantly less for a layer filling procedure, such as ten layers at a rate of one per day, than for a single fill procedure. He also reported that Barre and Hamdy (1974) considered a policy of adding grain continuously just ahead of the drying front, and concluded that drying was completed in a significantly shorter time than with a single fill. His main conclusions were that good management is required to achieve energy efficiencies better than those achieved by modern high temperature dryers, further experimentation is required to produce data to compare and validate the models, and further work is required to model the conditions and value of grain as a function of time, temperature and grain moisture content.

Muhlbauer et al. (1982) tested five low-temperature, in-bin drying procedures for drying early harvested wheat under central European

climatic conditions. The tests showed that intermittent fan operation using ambient air required less energy but longer drying time which resulted in a significant increase of mold population in the upper layers. It was concluded that this method is afflicted with higher risks. Their tests showed that continuous fan operation using ambient air yielded satisfactory results with regard to energy consumption, uniformity of moisture distribution in bulk and quality of the dried grain.

Colliver et al. (1983) developed a control procedure based on minimizing the overall operating energy costs of a LTD system by considering predicted weather conditions over two-hour periods. The maximum effective total heat change of the grain predicted over each two-hour period was used in a modified critical path method to select the control procedure. This procedure was compared with various control methods using computer simulation for five different systems. The energy savings of switching modes of operation compared to continuous fan operation ranged from 20% in the case of natural air drying system to 55% in the case where electric heaters were used. The simulation of the five different systems based on relative humidity and timer control indicated energy savings of 15 to 25% and 7 to 29%, respectively, compared to continuous fan operation. The authors indicated that an accurate, reliable, and inexpensive relative humidity transducer needed to be developed before relative humidity can become the switching parameter in an on-farm application.

Gunasekaran and Shove (1986) used dynamic programming to obtain the optimum daily airflow rate for natural air drying periods of 15, 20, 25 and 30 days. Unlike the optimization and fan management techniques suggested by Pfost et al. (1977) and Morey et al. (1979b), the main advantage of this technique authors was said to be the eliminated the risk of grain spoilage

by establishing limits on length of drying. It was found that total airflow requirement could be reduced by up to 15% using this method as compared to continuous operation. However, Colliver et al. (1983) pointed out that the main shortcoming of the technique is that the weather and its associated drying capabilities cannot be reliably predicted as far in advance as in needed for the slow, low-temperature drying process. Gunasekarnan and Shove (1986) considered constant drying air properties which make the validity of the solution questionnable. It was also not clear that a reduction in total airflow would provide corresponding energy savings for natural air drying systems because the specific energy requirement (kJ/kg) is much higher at larger airflow rates than would be required at certain periods with the optimum solution. Their optimum solution would be more appropriate with high temperature in-bin drying systems where the mechanical energy requirement to provide airflow is much lower than for heating the air.

Reid et al. (1986) developed a stochastic drying simulation model by combining a modified version of Thompson's equilibrium grain drying model (Morey et al., 1976) and a weather simulation model constructed for Blacksburg, Virginia by Kline et al. (1985). The model was used to simulated 100 years of corn drying from 18% to 15.5% (w.b.) for two fall starting dates and 6 drying air temperature above ambient. In addition to various site-specific conclusions, the authors stated that the use of stochastic weather data provided a broader view of what can be expected to occur during a drying season than is possible with average weather data.

The hardware, software and control criteria for microcomputer control of low-temperature corn drying was developed by Mittal and Otten (1981b). The required input for the control algorithm was the ambient air temperature

and relative humidity. The control criteria were tested using computer simulation against five other schemes, including Colliver's (1979) and Wilke's (1979) criteria. The results indicated better energy efficiency of the new control criteria over the existing ones while having comparable grain deterioration and overdrying levels.

The microprocessor controlled system was field tested by Mittal et al. (1982). The controlled bin used 14% less energy than the check bin which was ventilated using continuous fan operation. The only problem encountered with the system was with the humidity sensor. It was concluded that a reliable and maintenance-free humidity sensor was essential for the success of any microprocessor-based control system. As a result, Otten et al. (1983) selected and tested various humidity sensors to determine their accuracy and resistance to condensation and freezing. They found that two of the sensors were acceptable and compatible with the control system. Following completion of the field trials the control system was turned over to the Ontario Centre for Farm Machinery and Food Processing Technology for the development of a commercial product. Some work was performed in 1985 but various delays have resulted in little progress (Sterling, 1986).

A microprocessor-based controller has also been developed and tested by Persson and Churchill (1983). The system used inputs from a relative humidity transducer, a number of temperature sensors and a time-of-day clock to perform its control decisions. Very few details, however, were provided on the control algorithms by the authors. Field experiments were carried out and the results indicated a significant reduction in drying costs, improvement in grain quality and continuous protection from spoilage.

Morrison and Shove (1986) developed a microprocessor control system by modifying the control procedure developed by Colliver et al. (1983). They

performed computer simulations and experimental tests to compare energy use of this method with continuous fan operation. The drying simulation showed a 21.5% energy saving over continuous airflow drying and 28.4% over humidistat controlled electric heat drying. Actual drying experiments showed energy savings of 15% using the microprocessor controller compared with continuous flow operation. The authors also pointed out that for the system to be applicable to an actual farm operation the development of an accurate moisture sensing probe would be required.

Friday and Stroshine (1986) studied the effect of hybrid and kernel damage on mold development during low-temperature drying. Their results suggested that both hybrid and damage level affected the rate of mold development. These two factors had not been considered before in modelling of spoilage and grain deterioration in low-temperature grain drying.

1.2.2 STIRRING EQUIPMENT

In-bin drying systems may be equipped with vertical stirring augers. The augers move the grain from the bottom to the top of the bin to eliminate the drying front and keep the grain uniformly dry throughout the bin. This process makes it possible to use higher drying temperatures without causing excessive overdrying. The use of stirring augers also reduces the resistance of grain to airflow and results in higher airflow rates for the same fan size. The combination of higher temperature and airflow rates provides higher drying rates although the energy efficiency may be reduced slightly (Friesen et al., 1982).

Morey et al. (1979) studied the potential advantages of stirring augers for full-bin ambient air drying systems. They found that stirring lowered the maximum dry-matter decomposition in the bin so that grain with a higher

initial moisture content can be dried. Stirring intervals of one day (continuous), 7 days and 14 days were also investigated. It was found that dry-matter decomposition was not significantly affected by the stirring interval and that fan operation was reduced somewhat with higher stirring intervals. This observation and the potential settling out of fine material on the drying floor causing a decrease in airflow rate, resulted in the suggestion that stirring intervals of 7 to 14 days was preferable to continuous stirring. It was recommended that investment costs, however, for stirring devices should be carefully analyzed. Loewer et al. (1983) performed an economical analysis on the use of stirring devices for in-bin drying. Based on their analysis they concluded that adding stirrers was economical for low-temperature layer drying but not for natural air drying.

Wilke and Bern (1984a) monitored a stirred and an unstirred natural-air corn dryer for two seasons. They discovered that stirring initially decreased the resistance to airflow by 50%, and as corn dried, the resistance increased but not to the level found in unstirred bins. It was also found that stirring moved fines toward the drying floor and tended to form a crust which increased the airflow resistance. The results of two years of field tests with natural-air corn dryers reported by Wilke and Bern (1984b) showed that stirring two or three times [at filling, at 20% moisture (for corn wetter than about 22%) and at 15% moisture] reduced the drying time, energy use, overdrying and fan size requirement. Their future plans were to estimate the average long-term savings from stirring using computer simulations and to perform economic analyses to determine whether savings from grain stirrers justify their cost.

1.2.3. SOLAR DRYING

There has been a great deal of work done on low-temperature drying using solar energy over the last 15 years. A great variety of solar collector designs have been proposed and tested. It is the intention here to provide a general discussion of the applicability of solar energy as an alternative energy source for low-temperature drying based on current literature. Extensive literature reviews of the topic of solar energy applied to low-temperature grain drying have been reported by Foster and Peart (1976), Bakker-Arkema et al. (1978), Midwest Plan Service (1980), and Gunasekaran (1986).

The availability of solar energy and the performance of low-temperature drying are both very dependent on the geographical location. Since many of the results obtained elsewhere cannot be readily applied locally, the following discussion will mainly focus on the results of work applicable to Canada. A more general treatment of solar drying is presented in Section 4.2.

Wrubleski and Catania (1977) built and tested four identical covered flat-plate solar collector, each mounted on a circular grain bin, to determine the difficulty of construction, operational problems, energy collection and costs. Forty-five tons of wheat were dried from 16.5 to 14.5% m.c. in three weeks while collecting 812 kWh of solar energy. Although the collector was not difficult to build, a cost of $780 in materials and 108 man-hours of labor was required for its construction. Problems were also experienced with deterioration of the plastic covers during the winter and with dust accumulation inside the collector which added a significant maintenance cost. Wrubleski (1978) reported that the cost to attach a solar collector to a steel bin made this system

impractical.

Wrubleski (1979) also compared the performance of three different configurations of solar collectors for low-temperatre grain drying; namely, a round bin with a wrap-around collector, a square bin with collectors on the roof and wall, and an A-frame collector with rock storage. The square bin configuration was reported to be the most practical and most efficient design although a payback period of seven years was estimated. The A-frame and rock storage was too costly and the round bin configuration was difficult to construct. It was also reported that the collectors showed few visible signs of deterioration two years after construction.

Johnson and Otten (1980) tested two simular in-bin, low-temperature drying systems. One system used ambient air, the other one used solar-heated air. The solar collector was a bin-wall type. Although the solar air heater provided 4800 kWh of heat during 24 days of drying, the specific energy consumption was nearly the same for both systems. The main reason for this was that the fall of 1978, when the test was performed, was generally warm and dry. Under these conditions ambient air has a sufficient drying potential and further heating is not necessary. An economic analysis for poor drying seasons when the heat supplied by the solar collector would have been required showed that the total drying cost would be 20% higher for the 90 t solar dryer, assuming a 15 year life and 10% interest.

The potential energy savings using a solar collector for natural air grain drying system were simulated by Fraser and Muir (1980a) for the major grain growing regions of Canada. It was found that adding a solar collector to provide a temperature rise of 5°C reduced the mean energy consumed to dry wheat by 19% at Swift Current, 28% at Edmonton, and 33% at Winnipeg. In the

case of corn, the energy consumed was reduced by 16% at Winnipeg and 35% at London. The corresponding drying cost for each of these seven cases was reported by Fraser and Muir (1980b). By including an overdrying penalty, it was found that the average drying costs for all locations and conditions increased 6% by adding a solar collector. If the overdrying penalty was omitted, addition of a solar collector reduced the drying cost by an average of 2% for all cases.

Feddes et al. (1980) used a mathematical model to predict the drying capacity of solar-heated air as compared to natural air based on actual weather conditions at Edmonton. Their results indicated that solar heat accelerated the drying rate. For instance, the estimated time required to dry wheat from 20 to 14% moisture content with an airflow rate of 65.6 L /(s·/m^3) during the month of September was 18 days for natural air drying and 12 days when a solar collector surface of 1.72 m^2 per m^3 of grain was used. Their calculations were based on uniform drying throughout the bin as would be found using stirring devices. No economic analysis was performed. It is unlikely, however, that the benefit obtain from the higher drying rate would justify the cost of a solar collector and stirring equipment. The main benefit gained by using a solar collector is the energy saved by the reduction in fan running time, assuming that the extra time required with natural air is not critical to spoilage of the grain. Morey et al. (1979) reported that based on their simulation results, supplemental heat does not significantly reduce dry-matter decomposition in the top layer of grain in most years.

Winfield (1981) reviewed the research done on low-temperature solar grain drying in Canada. He reported that the Ontario results presented by Stone (1979) for corn and soybean drying indicated that simple free-

standing or on-bin solar collectors are not cost effective. Similarly to Johnson and Otten (1980), he pointed out that ambient air has sufficient drying capacity when the weather conditions are good.

It is therefore important to realize that during good drying years solar energy may not be needed. On the other hand, during poor drying years the grain may be wetter and there is less useful sunshine. This makes solar energy a less attractive proposition to dry grain.

1.2.4 CORN CRIBS

Corn cribs, which were popular during the forties and fifties, have progressively been replaced by shelled-corn drying and storage systems (Shedd, 1946; Sabourin, 1983). In the central region of the United states, the percentage of shelled corn went from 2% of the total crop in 1956 to 85% in 1975 (Foster, 1976; reported by Sabourin, 1983). The main contributing factors for this drop in popularity of corn cribs are (Sabourin, 1983; Brooker et al., 1978; Shedd, 1946; and Hilborn, 1981):

- twice the storage requirement;
- need of shelling before marketing;
- extra labour requirement for loading and unloading;
- damage by rodents and birds;
- limited harvest moisture content;
- high cost per unit volume; and
- snow control problems.

The higher cost of energy experienced over the last decade together with the higher quality of cribbed corn revived the interest in corn cribs. During this period various projects have been carried out to improve the design of corn-crib drying systems in the two major grain corn producing provinces of Canada. Some of the major advantages of conventional corn crib drying were listed by Sabourin (1983) and Rothwell (1984) to be:

- continuous harvesting without delay for drying;
- no fuel requirement for the drying process;
- the corn is dried and stored in the crib;
- very little management is required during the storage period;
- capital investment for the harvesting, drying and storing equipment is less than for shelled corn drying systems;
- preservation of product quality; and
- monetary value of the cobs after shelling.

Some of the main disadvantages of conventional ear corn systems could be resolved by improving the design and mechanizing of the crib. This would make the use of corn cribs more attractive to some corn producers. For instance, Benoit et al. (1985) reported that in Quebec 8% of the grain corn produced in 1980 was dried in cribs while in France, where efforts have been made to mechanize corn cribs, close to 20% of the grain corn produced for the same year was dried in cribs. In Ontario, only about 1 percent of the corn crop is dried and stored as ear corn (Columbus et al., 1985).

Hilborn (1981) reported on the testing of an ear corn handling and storage system. Three different methods to handle the ears from the corn picker to the elevator were considered: a gravity box, a forage wagon and a tilt box truck. The elevator consisted of a standard hay bale-corn cob conveyor. The crib was made of steel construction and elevated on piers leaving enough space below the false floor for the unloading conveyor. A three-point hitch unloading elevator which has the ability to extend itself laterally under the crib was designed, constructed and tested. One half of the crib was built with a roof to determine if roofing was necessary to control rain. The main observations resulting from two years of testing were reported by Hilborn (1981) to be:

- a conventional hay bale-corn crib elevator performed the job but it should be modified to increase the fines separation area;
- there seemed to be no problem with the 2 m width even with an initial moisture content of up to 30%;
- rodent control was better than the average crib due to the elevated false floor;

- a roof over the crib was considered to be necessary; and
- the elevated floor allowed the wind to flow under the crib which apparently eliminated any snow accummulating problem beside the crib.

The system was evaluated in the field and found to perform well. Recommendations, however, were made to develop a conveyor that could be used for both loading and unloading the crib. Modifications of existing conveyors were found to be expensive while not performing as well as desired.

The storage costs of ear corn and shelled corn were compared by Benoit et al. (1985). The estimated cost for a steel bin and a galvanized steel crib was $73 and $135/t of shelled corn, respectively. It was assumed that the cost of drying and trucking shelled corn to an elevator would be $28/t. Therefore, the extra investment for the corn crib would be recovered in three years.

Rothwell (1984) developed a containerized corn crib system. It consisted basically of 1.2 m cube boxes made of a wood or metal frame covered with wire mesh at the bottom and the sides. The boxes contained approximately 775 kg of wet worn and were handled using the front end loader of a tractor. The containerized system was tested and demonstrated at two farms in 1983 with the containers stacked to give a maximum crib height of 3.6 m and to provide storage for 45 t of cob corn. The inital moisture content in November was 26.0% and the final moisture content in May, 1984 was 11.6%. The grain quality was determined to be good. Although the cost of the containerized system was higher than a conventional crib, it had a saleable value, required less labour for filling and emptying, and caused less damage to the corn from handling which in turn resulted in less spoilage in the crib.

An economic analysis comparing the cost of various alternative methods

of harvesting and storing grain corn was also performed by Rothwell (1984). The analysis was made for the cases where 12, 40 and 120 ha of corn were grown. Only in the case of 40 ha did the conventional crib sytem required slightly lower operating costs per year. Hilborn (1981) also reported that the ear-corn system had about the same harvest and post-harvest cost per unit of shelled-corn as shelled-corn dried and stored at a conventional elevator.

Although the container system performed well and farmer response was reported to be good, the estimated cost of containers of $225 and $260 for the wooden and metal containers, respectively, was considered too high for farmer acceptance. Therefore, the wooden containers were redesigned and the cost reduced to $161 each in unassembled form. Preliminary testing of the redesigned container in harvesting, stacking and emptying operations indicated structural adequacy. Drying experiments in 1984 were also satisfactory (Agricultural and Energy Engineering Ltd. 1985).

Another crib elevated on concrete piers was tested by Sabourin (1983). The crib was equipped with a series of doors on the side for unloading. The floor of a section of the crib was modified to provide a 30^{o} slope on each side of the door. This modification reduced the labour requirement for unloading to one person. It was possible with this design to unload the crib directly into the corn sheller or to a grinder-mixer without using an unloading conveyor, thus reducing capital investment. Wire mesh was placed on the inside of the structure to eliminate the blocking effect of the structural members. A finer screen was placed on the outside to prevent access by birds. An economic analysis showed that the system was slightly cheaper than a conventional shelled-corn system. The size of farm for which

the difference between the two systems was the largest was a 75 ha farm.

Benoit et al. (1985) developed a commercial crib along with the associated handling equipment. The galvanized steel crib was prefabricated in modular sections in a shop and assembled on the farm. The floor of the crib was inclined to reduce labour requirements during unloading. The handling equipment consisted of a side-dumping wagon, a hopper to feed the cobs into the combine for shelling, a loading elevator and an unloading conveyor. The elevator and conveyor consisted of standard equipment adapted to the crib.

Columbus and Van Hooren (1985) monitored the performance of a structure for bulk storage and drying of ear corn using low-temperature, fan-forced air. The 500 t capacity structure was 30.5 m in length, 12.2 m in width and 4.8 m in height to the eaves. An axial fan located at each end of the structure supplied the air throught the corn ears from a slotted triangular shaped duct. The results of only one season of testing were not very promising because the corn required additional commercial drying which did not provide significant energy savings. A poor airflow distribution in the storage facility resulted from a concentration of detached kernels below the end of the conveyor.

Ferland et al. (1986) studied the drying of shelled corn in thin perforated cribs exposed to wind. Five different crib thicknesses were tested: 150, 300, 450, 600 and 750 mm. A set of cribs of a given thickness was placed perpendicular and another set parallel to the prevailing wind. It was found that at the end of the storage season about 30 to 50 mm of corn on each side of the crib had a dark colour due to mold growth. The authors reported that a perpendicular orientation provided more exposure to rain and sunshine and damage from surface mold was more pronounced. Nevertheless,

they recommended, that a perpendicular orientation be used and that corn should be well protected against rain and direct sunshine without interferring with air circulation. It was shown to be possible to dry 30% moisture content shelled corn in a 300 mm wide crib, or less, set parallel or perpendicular to the prevailing winds. No economic analysis was performed on the system.

1.2.5 SUMMARY

1. Low-temperature drying of grain involves temperatures at a near ambient conditions, which results in drying periods of up to several weeks. The process is basically a race between the movement of the drying front and grain spoilage.
2. Artificial low-temperature drying is done in storage bins equipped with perforated floors and a fan.
3. The relationship between drying time and such parameters as moisture content, weather conditions, filling rates, airflow rates and drying temperature have been researched extensively.
4. Guidelines are available to determine the minimum airflow rates for various conditions for some locations; however, guidelines for other locations are needed.
5. Increased drying rates may be obtained by increasing the drying air temperature a few degrees by adding energy in the form of solar heat or a resistance heater.
6. Various fan and heater management schemes have been investigated to improve the energy efficiency and reduce the risk of spoilage.
7. Microcomputer based control systems have been developed and tested by a number of researchers but few, if any, are commercially available. The main

problem appears to be the lack of a suitable relative humidity or moisture probe.

8. Stirring equipment has been used to eliminate the drying front and to keep the grain drying as a uniform batch. The advantages and disadvantages of stirring equipment in LTD have not been completely determined.

9. Solar LTD has generally proven to be more expensive than natural or electrically heated air drying.

10. Drying of ear corn in corn cribs has received renewed attention in recent years.

11. Various studies have been performed to improve the design of corn-crib drying systems; including the loading and unloading components. Additional work is needed.

12. Modular or container cribs have been designed and tested but none are produced commercially.

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1.3 HIGH-TEMPERATURE DRYING SYSTEMS

1.3.1 INTRODUCTION

High-temperature dryers (HTD) use a heated medium as the driving force to remove moisture from grain. Most HTD use air in the range of about 50 to 100°C depending on the design configuration but air temperatures of up to 290°C have been used in concurrent flow dryers (Bakker-Arkema et al., 1981). The main advantages of HTD are that high drying rates are achieved, minimal management is required, drying rate is not weather dependent and grain degradation by micro-organisms and grain respiration is minimal compared to low-temperature drying systems.

The major proportion of the grain dried in Canada in 1981 was done with HTD. In the case of corn and wheat, for instance, about 90% and 65%, respectively, was dried using HTD. In the Canadian prairies, however, natural air drying of wheat has become very popular over the last few years.

HTD systems are either used on the farm or by commercial operations. In Ontario about 70% of the corn is dried in commercial dryers while the remaining 30% is dried on-farm (Southwell and Rothwell, 1977). The typical capacity to dry corn by 10 percentage points is in the range of 2 to 5 t/h for farm dryers, while commercial dryers have capacities as high as 45 t/h (Bakker-Arkema et al., 1979). The drying capacity depends on the type of dryer, the operating conditions, the initial and final moisture content and the grain type.

There are many configurations of HTD and each has its own performance characteristics. The major basic configurations are considered below.

1.3.2 BASIC CONFIGURATIONS

(a) Crossflow dryers

In crossflow dryers the grain is contained inside perforated column(s) and the air is forced perpendicular through the grain bed. Crossflow dryers are either of continuous grain flow or batch type. In the continuous flow design wet grain enters the top of the column, slowly flows down in a packed bed by gravity, and leaves the bottom of the column at the desired moisture content. In a batch type the grain is either stationary in the columns or continuously recirculated from the bottom to the top of the unit until it is dried to the desired moisture content. Crossflow dryers are by far the most popular dryers, mainly because of their simplicity and low initial investment cost. The main disadvantage of the basic crossflow configuration, however, is that a large moisture gradient is created across the grain column. The grain adjacent to the side where the air enters the column overdries and reaches excessively high temperatures which causes stress cracks and breakage of the kernels. In conventional crossflow dryers the warmest grain encounters the coldest air in the cooling section which also induces stress cracks (Bakker-Arkema et al., 1973).

The energy efficiency, quality performance, capital cost and operating cost of crossflow dryers are greatly affected by the design parameters. In designing a crossflow dryer compromise must be made between drying performance and cost. Morey et al. (1976) used computer simulations to study the effect of drying air temperature and airflow rate on energy requirements and drying uniformity for the basic crossflow dryer configuration. It was shown that for a fixed drying temperature the energy required increased with increasing airflow rate, while moisture content differential decreased. It was also shown that for a fixed airflow rate,

the energy required decreased with an increasing air temperature while moisture content differential increased at the higher temperatures.

Gustafson et al., (1981) performed laboratory experiments to study the effect of airflow rate and temperature on the energy efficiency and quality of corn dried in a crossflow dryer. They found that the overall airflow rate had the most significant effect on energy requirement. For example, a 123% increase in airflow rate caused a 15.3% increase in specific energy consumption while an air temperature increase from 82°C to 138°C decreased energy used by only 5.2%. The grain quality indicators used by Gustafson et al., (1981) were breakage susceptibility, grain temperature, and cross-column variation in breakage susceptibility and moisture content. The effect of airflow rate and temperature on each quality parameter were discussed. In general it was found that air temperature has the most significant effect on cross-column variation in moisture content and breakage susceptibility and on final grain temperature. The average breakage susceptibility was affected more by final moisture content. It appears from these results that to minimize grain damage and specific energy use with a crossflow dryer lower airflow rate and temperature should be provided without excessively reducing the drying capacity.

Pierce and Thompson (1981) used computer simulations to study the effect of temperature and airflow rate on energy requirements, drying capacity and grain quality for the basic crossflow configuration. The moisture differential across the drying bed, the maximum average grain temperature and the maximum drying rate were used as grain quality indicators. Their simulation results confirmed previous research conclusions that energy requirements are generally reduced by increasing the

drying air temperature and reducing the airflow rate. On the other hand, it was shown that the moisture differential across the drying bed was lowest for high airflow rates and low drying air temperatures. Their results indicated that for a given drying air temperature there was a corresponding airflow rate which minimized the moisture differential across the drying bed and energy requirement.

Pierce and Thompson (1981) pointed out that while the minimum energy requirement and moisture differential are obtained at low temperatures and airflow rates, the dryer capacity was adversely affected. Their results also indicated that for a given air temperature there was a corresponding airflow rate which minimized the energy requirement while maximizing grain flow rate. It is clear from these results that a compromise must be made among drying capacity, energy efficiency and grain quality for the selection of drying temperature and airflow rate for a basic crossflow dryer configuration.

Grain column thickness is another important design parameter. Bakker-Arkema et al., (1973) stated that increasing the thickness of the grain column in a conventional crossflow dryer resulted in a larger moisture content differential across the column.

There are various field studies of grain dryers of the basic crossflow configuration reported in the literature. A summary of the performance characteristics and the range in the design parameters are found with those of other dryer configuration in Table 1.3.1.

(b) Mixed-flow dryers

A schematic diagram showing the flow of air and grain in a mixed-flow dryer is given in Figure 1.3.1. The dryer consists of a series of

alternating rows of air inlets and outlets located in the grain mass. The airflow is either concurrent or countercurrent to the grain from the air inlet to the outlet ducts. With this configuration there is no drying front and the grain dries more uniformly thus allowing higher drying temperatures. It is also possible to dry grains of any size and shape without structural modification to the dryer as there are no screens involved. Bruce (1984) pointed out, however, that initial contact with the large area of hot ducts may cause heat damage to grains during a typical contact time of 2 to 4 minutes.

Miller and Whitfield (1984) used computer simulations to study the effect of drying air temperature, airflow rate and dryer size on the grain throughput, specific energy consumption, and grain temperatures for the mixed-flow configuration. Their results showed that increasing the energy input to a given dryer by either increasing the air temperature or airflow rate increased grain throughput. Higher temperatures provided lower specific energy consumption while higher airflow rates increased specific energy consumption. It was also shown that for a constant energy input, increasing either the dryer size or number of grain beds in the dryer improved the specific energy consumption and grain throughput. The results of field testing of mixed-flow dryers are presented with others in Table 1.3.1.

(c) Concurrent-flow dryers

As shown in Figure 1.3.1 in concurrent-flow grain dryers the air enters the grain mass through a series of horizontal ducts and flows in the same direction as the grain. In concurrent-flow dryers cooling is usually done in a countercurrent fashion. The cooling air enters a series of horizontal

ducts at the bottom of the dryer, flows countercurrently through the grain mass and leaves the dryer along with the drying air through another set of horizontal ducts. Much higher drying air temperatures can be used in concurrent-flow dryers since the air enters the grain mass at the location where the grain is at the highest moisture content. The use of higher temperatures makes the concurrent-flow dryer very energy efficient. Typical energy consumption for a concurrent-flow dryer is 20-25% less than for a comparable crossflow dryer (Brook, 1979). The quality of grain dried in a concurrent-flow dryer is usually also very good mainly due to countercurrent flow cooling. With countercurrent-flow the grain is cooled slowly, thus minimizing the temperature gradient in the kernel and reducing stress cracks and breakage.

Bakker-Arkema et al., (1984) applied a dynamic programming technique to the optimization of concurrent-flow dryer design. The optimal design was compared with that of a commercial dryer using a computer simulation. The results indicated that it is advantageous to operate the dryer at high air temperatures and to lower the airflow rate.

Westelaken (1978) also used a dynamic programming technique to optimize the drying air temperature, airflow rate and drying length for a single stage, a two-stage and a three-stage concurrent-flow dryer with three different ranges of drying capacity. In the case of multi-stage designs a tempering zone was included between each drying stage. It was found that the optimum tempering period was 1.25 hours long. Field testing of pilot scale concurrent-flow dryers was performed for corn, wheat and beans, and results were used to validate the simulation model.

Brook (1979) used computer simulations to study the effect of staging of concurrent-flow dryers. It was shown that energy efficiency between

single stage and multi-stage design is not significantly different. For the same drying capacity the multi-stage dryers were found to have a lower capital cost than the single-stage design. The effect of recycling the exhaust air from one drying stage to the heater of the next drying stage was also considered. It was found that the extra humidity in the inlet air had little effect on the drying rate while recycling decreased energy consumption.

Due to the higher air temperature in a concurrent-flow dryer the airflow rates are usually lower which results in less air pollution (Westlaken, 1978). Brook (1979) indicated, however, that lowering the airflow rate in concurrent-flow dryers increased grain temperature and reduced grain quality.

Bakker-Arkema et al. (1981) stated that concurrent-flow dryers are characterized as low total airflow - high static pressure devices with similar horsepower requirements as those of crossflow dryers. They tested three commercial corn dryers for energy efficiency and grain quality over a two-year period. The first dryer was a crossflow dryer with reversed airflow and air-recycling. The other two were concurrent-flow dryers: a three-stage continuous flow type and a batch type with internal grain recycling. Their results showed a 25% greater energy efficiency and 20% lower breakage susceptibility for the concurrent flow units.

Bakker-Arkema and Schisler (1984b) studied the effect of various design parameters on the temperature and moisture content of grain during countercurrent-flow cooling. A mathematical simulation model was developed, and compared favourably with experimental results. Using the mathematical model they have shown that the final grain temperature was significantly

affected by airflow rate, grain flow rate, the cooling air inlet temperature, initial moisture content and the grain type and hybrid.

(d) Countercurrent-flow dryers

In countercurrent-flow configurations the air flows parallel to the grain but in an opposite direction. Countercurrent-flow grain dryers usually consist of a steel bin with a perforated false floor in which grain is loaded from the top and unloaded at the floor level with a sweep auger. Cooling is performed in another bin, which makes it usually impractical to recirculate the cooling air into the dryer. On the other hand, higher temperatures can be used than in a batch-in-bin system without overdrying the bottom layer of grain. The unit can also be coupled with dryeration to preserve grain quality, increase drying rate and reduce energy cost (Baker et al., 1981).

Bridges et al. (1984) used computer simulations to study the effect of drying air temperature, bin diameter, grain depth, moisture removal, and fan power and type on the drying rate and energy use of a continuous flow in-bin drying system. The point of optimum performance was defined as the grain depth where the maximum drying rate occurred for any set of drying parameters. It was found that for all parameter sets, the drying rate was reduced (in some cases significantly) while energy use decreased slightly as grain depth increased past the optimum performance point. It was also shown that increasing the drying temperature provided higher drying capacities and decreased the energy efficiency for more than 10 points of moisture removal. For a moisture removal of 5 percentage points it was found that increasing the drying temperature may cause an increase in the energy use.

1.3.3 INNOVATIVE DESIGNS

(a) Temperature staging

As mentioned earlier, increasing the drying air temperature in a dryer improved its efficiency. Grain is able to tolerate a higher drying air temperature at the beginning of the drying period when the moisture content is the highest. This suggests that temperature staging could improve the dryer efficiency without affecting the grain quality. In continuous flow dryers temperature staging consists of dividing the drying column in multiple stages and providing decreasing air temperatures from the top to the bottom. In the case of batch dryers, temperature staging is implemented by decreasing the temperature by steps from the beginning to the end of the drying period.

Gustafson et al. (1981) studied the effect of temperature staging on drying efficiency and quality of corn produced by crossflow dryers using a laboratory-scale experimental dryer. The experiments consisted of reducing the air temperature from 149 to 110°C in fourteen equal steps of 2.8°C. The results showed that temperature staging does not appear to have a significant effect on energy use. The results also showed that staging increased the moisture gradient across the column by 0.4 percentage points on the average, the breakage susceptibility increased to 28.7% from 23.8% and the grain temperature gradient was 78% compared to 75%, all compared to the constant temperature drying at 110°C.

Jones (1986) studied the effect of temperature staging for inlet temperatures of 116, 121 and 127°C with temperature reduction of 5.6, 16.7 and 27.8°C halfway through the drying section. His results showed that the same trends held for all three initial inlet air temperatures. It was found

that decreases of 5.6, 16.7 and 27.8°C in the inlet temperature resulted in decreases of approximately 4.5, 14 and 22°C in the average grain temperature, respectively. The effect of temperature staging on the moisture differential, however, was found to be small. Decreases of 5.6, 16.7 and 27.8°C in the inlet air temperature caused the moisture differential to decrease by 3%, 10% and 20%, respectively.

(b) Reverse airflow and grain inverters

Paulsen and Thompson (1973) used computer simulations to study the effect of drying air temperature and airflow rate on the moisture gradient across the column, the average grain temperature at the end of the drying period and the drying efficiency of the basic crossflow configuration with and without airflow reversal in the drying section. It was shown that there can be a significant reduction in moisture gradient and a slightly lower grain temperature with reversed airflow. It was also found, however, that reversed airflow can cause a reduction in drying capacity of 2 to 8%, depending on the temperature, and slightly decrease the energy efficiency.

Bakker-Arkema et al. (1973) used computer simulations to study the effect of section length, grain column thickness and drying air distribution in a reversed airflow grain dryer. To validate the model a dryer with the same configuration and manufactured by the Hart-Carter Company was tested and compared with the simulation results. The maximum moisture gradient across the drying column was 5.3 percentage points and occurred at the end of the first section of the dryer. The moisture gradient at the bottom of the cooling section was found to be only 1.9 percentage points which was said to be significantly lower than for conventional crossflow grain dryers. It was also found that the maximum moisture differential increased by less

than one percent when the column thickness was enlarged from 0.23 to 0.30 m.

Pierce and Thomson (1981) used computer simulations to study the effect of airflow rate and drying air temperature on the performance of four crossflow grain dryer types including the basic configuration and one with reversed drying airflow. Their results were consistent with those of Paulsen and Thompson (1973). They found that there is a decrease in capacity and an increase in energy consumption for a reversed crossflow dryer operating at the same temperature and airflow rate as compared to the performance of a conventional crossflow dryer. These differences were found to be less than 2 percent at low temperatures but increased with drying air temperature. Pierce and Thompson (1981) pointed out, however, that the major difference between the two dryer types was the lower moisture differential with the reversed airflow crossflow dryer. For example, the moisture differentials for the conventional and reversed airflow dryers at an airflow rate of 40 $m^3/min.m^3$ of grain and drying air temperature of 100°C are 10 and 4 percentage points, respectively.

Davila et al. (1983) used computer simulations to study the effect of reversing airflow direction in a fixed-bed rice dryer. They found that the optimum reverse time interval was 54% of the total drying time. Their results were consistent with others. A considerable improvement on the final distribution of the moisture content while slightly lower energy efficiencies were obtained by reversing the airflow direction.

To physically change the direction of airflow midway through the drying section of a crossflow dryer requires major design changes. In order to provide approximately the same effect as reversing the airflow, some crossflow dryers have been equipped with grain inverters which move the grain from one side of the column to the other side.

Otten et al. (1980) monitored a commercial crossflow grain dryer equipped with a grain flow inverter located at one third of the total length from the top of the column. The results of these tests were used to validate the computer model that was used to study the effect of grain inverters. The grain inverter was shown to reduce the temperature and moisture gradient across the drying column while causing a slight decrease in capacity and a 2% reduction in energy efficiency.

Gustafson et al. (1981) studied the effect of grain inverting on energy efficiency and grain quality using a laboratory dryer. The grain bed consisted of three superimposed layers and grain turning was simulated by interchanging the bottom and top layers. The grain was turned at the one-third and two-third points of the total drying time required without turning. They found that turning the grain twice did not appear to have a significant effect on energy use but decreased the moisture content gradient across the column by an overall average of 4.1 percentage points, reduced the breakage susceptibility gradient across the column from 46.6 to 27.7% and reduced the average final grain temperature by 7 ^{o}C.

Jones (1986) used simulations to study the effect of grain turning on moisture differential and the grain temperature for various bed thicknesses. It was found that for a bed thickness of 310 mm, one, two and three grain inverters caused a decrease of 53%, 48% and 63% in the moisture differential across the column, respectively, when compared to no grain inverters. It was also found that one grain inverter resulted in minor increases in energy consumption but lowered the average grain temperature by as much as 10 ^{o}C. It was, therefore, concluded that only one inverter should be used.

Another method used to reduce the moisture gradient across the column is the differential - speed design. The term refers to crossflow dryers in

which the grain closest to the air inlet side moves at a faster rate through the column than grain located at the exhaust side (Lasseran, 1982). Dual discharge rolls located under each drying column rotate at different angular speeds so that the grain speed ratios can be varied from 1:1 to 1:4. Kuppinger (1980) showed that the moisture differential across the column was halved by changing the grain-speed ratio from 1:1 to 1:3. Bakker-Arkema et al. (1982) found that the optimum grain-speed ratio depends on the grain type and initial moisture content. A commercial crossflow dryer using differential-grain speed, tempering and air-recycling was testeed and the specific energy use was found to be 3800 kJ/kg.

c) Grain tempering

During drying a moisture gradient is developed within the grain kernel. At this point moisture will move from the center to the surface by mass diffusion as the result of a concentration gradient. It is therefore possible to stop the airflow for a period of time and let the grain temper.

(i) tempering before cooling

It has been hypothesized that providing a rest or tempering period before cooling the grain would reduce stress cracking because of a reduction in moisture gradient. It would also increase the moisture removal during cooling and result in a higher cooling rate due to moisture evaporation from the kernels.

The tempering process appears to have been introduced by Sabbah et al. (1972) and is similar to the dryeration process developed earlier by Foster (1964). Sabbah et al. (1972) studied the effect of tempering time on the cooling rate and on the moisture removal during the cooling of dried corn.

Tempering periods of 1,2 and 4 hours were compared to no tempering. They found that as tempering time increased the total amount of moisture removed, the rate of moisture removal and the rate of cooling increased. It was also found that the effect of tempering was more pronounced at lower airflow rates.

Gustafson et al. (1983) studied the effect of short-term (0 - 60 min.) tempering of corn before cooling on breakage susceptibility and moisture removal during cooling. The effect of tempering was studied by performing thin-layer and deep-bed drying experiments using a laboratory-scale dryer for three dryer configurations (cross-flow, cross-flow with grain turning and mixed-flow). They found that for thin-layer experiments breakage susceptibility was significantly affected by tempering time and final moisture content. It was also found that most of the effect of tempering on breakage susceptibility reduction was at the earlier stage of tempering. For instance, 68% of the decrease in breakage susceptibility occurred in the first 15 minutes of tempering. The tempering time also affected the moisture removal during cooling and approximately 50% of the improvement occurred in the first 15 minutes of tempering. The results of the tests for the three dryer configurations showed a significant reduction in breakage susceptibility and moisture content removal with increasing tempering time. The dryer configuration effect was not significant in the case of moisture removal while the tempering time affected breakage susceptibility the least in the case of the mixed-flow dryer. Tempering improved the efficiency of the drying process to varying degrees with all three drying configurations.

(ii) tempering during drying

Hall and Anderson (1980) presented a description and performance

results of a unique dryer in which two tempering sections were used. The unit was based on the concept of using multiple grain passes through the concurrent drying zone and counterflow cooling zone. A steeping gainer was placed ahead of the drying zone and a steeping zone ahead of the cooling zone. Since the dryer operated as a batch unit, it was referred to as the BIRD (an acronym for Batch Internal Recycling Dryer). Aside from providing accurate control of the final moisture content and a high quality product, the specific energy use averaged 3250 kJ/kg of water removed. A further reduction in energy use could be achieved with energy recovery from the exhaust gases. Although the tests of the prototype unit were successful and a number of design features patented, the dryer has not been marketed by the Andersons.

Harnoy and Radajeski (1982) studied the effect of providing tempering periods at regular time intervals throughout the drying process on the drying efficiency and the final grain quality for various temperatures and air velocities. The tests were performed on grain beds of 300 mm thickness using a laboratory-scale dryer. It was found that the thermal efficiency was increased as the blowing ratio increased up to eight (the blowing ratio was defined as the ratio of the cycle time to the blowing time). Although the moisture content differential across the grain bed increased with the introduction of tempering periods, the energy consumption decreased considerably. For instance, at an air velocity of 0.2 m/s and an air temperature of 60°C, the specific energy decreased from approximately 5250 to 4400 kJ/kg, while the percentage of kernel cracking decreased from 11 to 10% when compared with no tempering.

Button (1982) reported on a system referred to as sweat boxes or preheat modules added to continuous crossflow corn dryers. The preheat

module consisted of a set of two grain columns equipped with an axial fan and a burner in the same configuration as the continuous crossflow above which it was installed. The top 1.2 m of the column was perforated while the bottom 0.9 m was made of solid sheet metal and served to provide a tempering period. The system described by Button (1981) in 1981 consisted of three of these units stacked one above another on top of the dryer. The top burner was set to provide the drying air at 104 °C while for each successive stage the temperature was reduced by about 6 °C. The dryer reported by Button (1982) in 1982 was equipped with only one preheat module. Unfortunately, the performance of these drying systems was not tested and only qualitative statements were made. It was said that the preheat modules increased drying capacity, improved the fuel efficiency and reduced kernel stress cracks.

(iii) dryeration

The dryeration process was developed at Purdue University by Foster (1964) for corn drying in an effort to improve quality, decrease specific energy consumption and increase dryer capacity. The process consisted basically of drying shelled corn in a conventional high-temperature dryer to about 16-18% moisture content, transferring it to a bin where a tempering period is provided followed by aeration to cool the corn and further reduce its moisture content. The corn is then transferred to a storage bin. Thompson and Foster (1969) reported that a combination of 8 h of tempering and aeration at 95 L/s.t provided the highest moisture removal. They also reported that corn heated to 60 °C in the dryer and allowed to temper, lost about 2 percentage points of moisture during aeration cooling.

A demonstration project supported under the ENERDEMO program in Quebec

compared the drying performation of a conventional continuous mixed-flow dryer with a dryeration system using the same dryer (Audet and Lamontagne (1984)). A series of four tests were carried out for each drying system with approximately 100 tonnes of corn dried during each test. The results showed an increase in drying capacity from 8.5 to 16.8 t/h and a decrease in specific energy consumption from 7010 to 4484 kJ/kg using dryeration instead of the dryer alone. Their economic analysis showed a payback period of two years for the extra equipment required for dryeration, assuming an increase of 5% in corn price is obtained for better quality.

Brooker et al. (1974) reported that in one dryeration test by McKenzie et al. (1967) the percentage in stress-crack formation and kernel breakage of grain corn was 7.6% compared to 43.6% with conventional drying and cooling.

The energy savings obtained by dryeration is mainly attributed to the efficient use of the sensible heat of the corn to evaporate the last few percentage points of moisture during aeration cooling. An alternative to dryeration as a means of using the sensible heat from the corn consists of recirculating the cooling air and the unsaturated portion of the drying air in a continuous dryer (see section 3.2). It is not clear, therefore, that dryeration is an energy saving practice compared to air recirculation. The main advantage of dryeration is the increase in drying capacity and the improvement in grain quality. As a result, dryeration is used by many farmers as well as some elevator operations in drying grain corn.

d) Cyclic drying

Cyclic drying consists of alternating between heated and unheated air during drying. The main difference between cyclic drying and grain

tempering is that in cyclic drying air is supplied continuously. This practice was investigated by Browning et al. (1971) as a means of reducing overdrying and moisture differential across the grain bed in a batch-in-bin drying system. It was hypothesized that during the portion of the cycle when heat is used a layer of grain is warmed, this grain heats the cooler incoming air during the remaining portion of the cycle, the warmed air carries heat into the grain above and the drying zone is either never established or it has greater than normal thickness. Two in-bin dryers were tested by Browning et al. (1971), one in which constant heat was supplied and the other in which heat was supplied only 75% of the time. Four different cycling periods were tested; namely, 3, 4, 6 and 12 minutes. Their tests showed that the shorter time cycles of 3 or 4 minutes seemed to be more effective in reducing overdrying and moisture differential than when larger time cycles or continuous heat was used.

Ezeike and Otten (1981) performed a theoretical analysis of the tempering phase of a cyclic drying process. It was shown that when unheated air is passed through the grain during the tempering period, the grain temperature decreased and a larger amount of energy was needed to raise the enthalpy of the grain to the original drying level. It was concluded that more energy would be required and there would be an advantage in allowing the kernels to temper in quasi-stationary air.

Stefanovic et al. (1986) described the theoretical and experimental analysis of a high-temperature dryer which was designed a decade ago to allow grain to be exposed to drying air in a cyclic manner. The modular dryer consisted of a number of started sections, each 3 x 3 x 1 m. Each section was made up of seven grates and each grate (0.14 m high) was an

assembly of inverted truncated pyramids. The grates were arranged so that grain from a pyramid in an upper grate would flow into three pyramids in the lower grate. The drying air flowed perpendicular through the grain between the grates. Therefore, the grain was only exposed to the air while falling from one grate to the next and was allowed to temper while passing through the pyramids. The active drying period in each was about 1/23 that of the tempering period. The number of sections depended on the required capacity and varied from 4 to 12 for the drying zone and 4 for the cooling zone. The energy consumption without recycling was similar to conventional high-temperature drying. About 300 dryers were said to be in operation in Yugoslavia.

1.3.4 HIGH TEMPERATURE CORN DRYERS FIELD TESTS

A summary of the results of field testing various configurations and sizes of high-temperature grain dryers is presented in Table 1.3.1. All the tests were performed with grain corn and the results are presented by type of configuration and in order of increasing size of drying capacity.

The dryer performance is presented in terms of drying capacity and specific energy consumption. Although the loss in grain quality is one of the most important performance factors, it was not included in this report due to the lack of quality data. Also, the basis of quality loss, when reported, was not consistent among the various reports.

The drying capacity is given in metric tonnes of dry corn per hour. In the case of continuous flow dryers the drying capacity was measured as the grain throughput under steady-state drying conditions. The drying capacity of batch dryers included the time for filling, drying, cooling and discharging the grain. In the literature the drying capacity was given in

various volume or weight units and either for the wet or dry corn. The conversion was made on the basis that a bushel of corn has a volume of 1.25 ft^3 and weighs 56 pounds at 15.5% (w.b.) moisture content.

The specific energy consumption is given as the energy required per kilogram of water evaporated. It includes the thermal energy used to heat the drying air and the mechanical energy required for the fans and the grain handling equipment. The thermal energy was provided either with propane or natural gas while the mechanical energy was provided by electric motors or the power take-off of a tractor.

The variables that are considered to have a significant effect on the dryer performance are also noted. These include the ambient air temperature, the grain initial and final moisture content, the drying air temperature, the airflow rate and thickness of the grain bed. Comments are also included regarding the particularities of the dryer design as well as other factors that could have an effect on the dryer performance.

The Prairie Agriculture Machinery Institute (PAMI) adjusted the drying capacity and specific energy consumption for standard ambient temperatures, initial and final moisture content. The values listed in Table 1.3.1 are the adjusted one.

1.3.5 HIGH TEMPERATURE DRYER CONTROL

Overdrying of grain is undesirable because it reduces the dryer throughput and increases grain damage and specific energy consumption. On the other hand underdrying may result in serious storage problems. In most high-temperature continuous-flow dryers the outlet moisture content is controlled by adjusting the grain flow rate through the dryer.

Another important purpose of grain dryer control is to minimize grain

damage. This is usually done by adjusting the drying temperature since the level of damage to grain increases with temperature. However, it is well known that energy efficiency and drying capacity of grain dryers increase with drying air temperature. Therefore the temperature is usually set to maintain the maximum temperature possible without causing damage to the grain based on its end use.

The main problem with grain dryer control is due to the unsteady state operation of most grain drying systems caused by variations in inlet moisture content. This problem is predominant at grain elevators where every grain load comes from different farms which results in large variation in initial grain moisture content. Other factors that have an effect on dryer control are the grain properties (Levesque et al., 1986), grain cleanliness and ambient air conditions.

The drying air temperatures of conventional continuous and batch type crossflow dryers are usually manually controlled. The drying air temperature is often monitored and thermostatic control is used to activate a modulating valve in the gas supply line to control the flow of fuel to the burner and thus the drying air temperature.

The grain throughput of continuous-flow dryers is usually controlled manually by adjusting the metering roll speed with variable speed DC motors. In most operations the operator takes a measurement of the outlet moisture content every 15 or 30 minutes and adjusts the metering roll accordingly to obtain the desired outlet moisture content. In some continuous-flow, farm-scale dryers the metering rolls are activated by a temperature controller that monitors the grain temperature near the drying section outlet. The operator adjusts the grain temperature controller based on the desired outlet moisture content.

The final moisture content in batch type grain dryers is usually controlled either by a timer or a thermostat. In the case of timer control the time setting depends on the grain type, the initial moisture content and the drying air temperature. It is set according to a chart supplied by the dryer manufacturer. With thermostatic control the burner is shut off after the grain reaches a specified temperature that should correspond to the desired moisture content.

Zachariah and Isaacs (1966) used computer simulations to test four different control strategies for a continuous-flow dryer; namely, a Proportional-Integral-Derivative (PID) feedback control, feed-forward with PID feedback control, an ON/OFF feedback control and a control system incorporating the PID and the ON/OFF control. Each control strategy was optimized by finding the proportional gain and reset time constants which provide the minimum value of the integrated product of drying rate and error squared resulting from the response of the system to a step change in initial moisture content. They found that a system optimized for one set of drying conditions could be very unstable under other conditions. They concluded that simulation of the drying process with the computer model provided a rapid and accurate method for investigating the performance of control systems. They found that the response of the optimal control system employing a feed-forward open loop showed little improvement over the feedback system used alone and that the improvement was not sufficient to justify the additional equipment that would be required.

Borsum and Bakker-Arkema (1982) developed a microprocessor-based control system to control the grain flow rate in a single stage continuous concurrent-flow dryer based on the outlet air and grain temperature. On-

line measurement of grain moisture content which is both relatively inexpensive and sufficiently accurate for control purposes is not yet possible with commercially available instrumentation (Borsum, 1981; cited by Borsum and Bakker-Arkema, 1982). The control algorithm used for the control system was a digital equivalent of the Proportional-Integral (PI) feedback strategy. The microprocessor controller was able to maintain the average outlet grain temperature of a pilot-scale concurrent-flow corn dryer within 0.5°C of a pre-selected set point value which corresponds to an average outlet grain moisture content of + 0.2% w.b. from the desired value. Borsum and Bakker-Arkema (1982) proposed that a temperature sensor to detect changes in the inlet grain temperature should be used as a feed forward control signal to reduce the effect of variable inlet temperature on the grain temperature(s) being used as the controlled process variable.

Stone (1983) used computer simulations to compare Feedforward (FF) control with conventional Proportional Integral control. The drying air temperature was used as the controlled variable to control the outlet moisture content. The integrated sum of squares of error (ISE) between the desired outlet moisture content and simulated moisture content was used to compare the performance of the controllers. Their results showed that the PI controller performed better than the simple FF controller. Stone (1983) tested the FF controller by delaying the FF controller response by one half the dryer dead time. He found that the FF controller with delayed action had 26% of the ISE of simple FF control and 48% of the ISEW of the conventional PI controller. He pointed out that FF controller does not adapt to changes in the dryer characteristics that occur with time and a combination of feedback and feedforward control or adaptive FF controllers may be the best alternative.

Becker et al. (1983, 1984) developed a simplified process model for continuous crossflow grain dryers to be used with a microcomputer. The model compared well with a more rigorous distributed parameter model and was used in an optimization study in which operating cost based on fuel and labor cost was minimized. It was found that the operating temperature was the limiting factor. They also performed a laboratory study on corn burning and found that 117°C was about the maximum temperature that should be used in crossflow grain dryers.

Forbes et al. (1984) developed a model-based control strategy for commercial grain dryers using the simplified process model developed by Becker et al. (1984). The simplified model used was the following:

$$W = W_i \, e^{-At}$$

where,

W = moisture content (dry basis, %)

W_i = initial moisture content (dry basis, %)

A = grain drying characteristic (s^{-1})

t = drying section residence time (s)

Feedback linear filtering was used to determine the grain drying characteristic. A total of four different control strategies were tested and compared using computer simulations; feedback from the dryer outlet (PID), lead/lag feedforward from the hot zone inlet and model-based feedforward of the average inlet moisture of the corn currently in the dryer's hot zone. The performances of the four different methods were compared using the sum of squared differences between predicted outlet moisture and outlet moisture setpoint using actual drying data as the input for the computer simulation. The only controlled variable was the metering

roll speed, while the drying air temperature was kept constant as it is limited to the grain end use.

It was observed that the PID feedback and the feedforward control strategies gave poor responses. This was attributed to the large system dead times and the high frequency of the inlet moisture variations. The authors pointed out that the major problem with both of those strategies is that the response was based on the corn which most recently entered or left the dryer. It was also found that the controller providing the best performance was the model-based strategy using an inlet moisture content as an arithmetic average of the measured inlet moisture for all the grain which is or will be in the dryer hot zone during the control interval. Forbes et al. (1984) instrumented and tested a full-scale grain dryer with the model-based feedforward control system. Their results showed significant improvement over manual control.

The control system developed by Becker et al. (1983) was put into commercial production by Rolfes Canada Inc., Waterloo. Since 1984 about fifty control systems were installed with the assistance of government grants through the Ontario Grain Dryer Retrofit Assistance Program. After evaluating the effectiveness of the program, White and Phillip (1987) reported that the reduction in energy assumption at monitored dryers was 13.5%; however, no details were provided as to the method used to monitor the dryers nor as to the basis of comparison. They also reported that 95% of the surveyed users noted increased dryer capacity, 97% reported less over drying and 81% claimed higher grain quality with the controlled dryers. Unfortunately the type of questions posed by the interviewer would tend to lead the respondents. Furthermore one would expect the various claims after tens of thousands of dollars were spent with energy reduction, capacity

increase and quality improvement on the objectives. Only carefully monitored runs would provide information on the effectiveness of the control system.

Whitefield (1986) used computer simulations to obtain the optimum parameters for a proportional and integral feedback controller of a concurrent-flow dryer. The throughput of the dryer was controlled based on the output moisture content of the grain. Data were obtained from a concurrent-flow dryer to test the validity of the simulation. It was shown that the absolute difference between actual and predicted values was within 1% point in moisture content (d.b.). Simulations were also performed with various values of grain and integral time constants to obtain the best performance. Actual data from farm tests were used as the input to the computer simulation in testing the optimized controller. It was found that the control system worked well for some, but not all, conditions. This was partly attributed to the non-linear relationship between throughput and drying.

Nybrant and Regner (1985) developed an adaptive microprocessor-based controller. A laboratory-scale batch dryer was used to study the effect of airflow rate and drying air temperature on the relationship between exhaust air temperature and grain moisture content. This was to evaluate the possibility of using the exhaust air temperature as a means of determining the outlet grain moisture content for the controller. They found that even with a constant temperature of the exhaust air, variations in the inlet moisture content will give variations in the final moisture content. The adaptive controller was tested using their laboratory-scale dryer. The experiments showed that the adaptive controller, in spite of varying

conditions, was able to accurately control the temperature of the exhaust air.

Brook and Bruce (1986) reviewed the most recent work on grain dryer control. They pointed out that acceptable grain drying computer simulations have been developed and are being used to investigate grain dryer control. They also pointed out that simulation models should be improved so that they are capable of calculating the damage to grain during drying. The accuracy with which grain conditions and hence grain quality can be computed is not yet acceptable and this is an active area of research. They stated that increasing demands for high quality grain in the world market dictates that grain drying research must develop better descriptions of grain quality as affected by conditions during drying. They proposed that rapid, on-line methods of sensing quality-related parameters are needed.

Eltigani et al. (1986) tested a microprocessor-based automatic controller for two seasons on a commercial crossflow dryer. The unit used semi-continuous moisture measurements with a model-based feed forward control algorithm with feedback trim. Compared to manual operation the unit resulted in less overdrying, improved grain quality, lower labor requirements and decreased energy consumption.

Brown et al. (1987) described the development and farm testing of a computer-based control system for a batch-in-bin grain dryer. In 1985 nine drying tests were conducted with wet corn harvested at about 30% initial moisture content (wet basis). The control system utilized an inexpensive personal computer (Radio Shack TRS-80 Model 100) and an A/D interface unit designed to communicate with the computer through the RS232 port. The control algorithm was based upon simulation of the drying process with known initial conditions and parameters. Control to within 0.3 percentage

points of the target moisture content of the dried corn was realized in three of the tests.

Some modifications have been made to make the software more user-friendly and to allow for continuation of drying after a power failure. Three prototype units were built by Process Instrument Systems Ltd. Toronto, and were tested by farmers during the fall of 1987 (Otten, 1987).

1.3.6 SUMMARY

1. A considerable amount of experimental research has been done to study the effect of airflow rate and drying temperature on energy efficiency, dryer capacity and grain quality for all types of high-temperature dryers.
2. Similarly, mathematical models have been developed to simulate the drying process in those dryers.
3. For crossflow dryers it has been shown that at a fixed drying temperature the energy consumption increased with increasing airflow rate, while moisture content differences across the column decreased. On the other hand at a fixed airflow rate, the energy consumption decreased with an increase in drying air temperature, while the moisture differential increased. Similar observations have also been made for mixed-flow dryers.
4. Concurrent-flow dryers allow the use of much higher air temperatures than crossflow dryers because the hottest air comes in contact with the wettest grain. As a result the energy efficiency of concurrent-flow dryers is 20 to 25% higher while the grain quality is better, especially when countercurrent flow cooling is used. Simulation and experimental studies have shown that concurrent-flow dryers are most

efficient at high drying temperatures and low airflow rates.

5. Multi-stage concurrent-flow dryers have been developed with tempering zones between each drying stage. Although this staging allows recycling of the exhaust from one stage to another, the effect on efficiency is minimal as compared with single stage units.

6. Countercurrent-flow dryers are usually large steel bins with perforated floors in which grain is loaded from the top and unloaded continuously at the floor level with a sweep auger. These units provide considerable flexibility in operating conditions and because of the deep bed (1 to 2m) the energy efficiency is higher than for most other dryers. Cooling of the grain is normally done in storage bins.

7. Various design modifications have been made to the various basic high-temperature dryer configurations with the objective of improving energy efficiency and grain quality. These include use of temperature staging, reversing the airflow or installing grain inverters at different levels in crossflow dryers, allowing grain to temper before cooling or at various drying stages. Most of these innovations have been successful and most commercial dryers are manufactured with the innovations as part of the basic design or as options.

8. Research has also been done to develop dryers based on cycling the drying air. A commercial dryers using this principle is available in Yugoslavia.

9. Other attempts at improving dryer efficiency include use of heat recovery systems and alternate energy sources (see chapter 4). Some of these modfications have been successfully applied, others are economically not feasible.

10. The most recent work on high-temperature dryers deals with the development of automatic control systems. This work is aimed at improving energy efficiency and grain quality by reducing overdrying and at decreasing labour costs. Although some microcomputer and microprocessor-based control systems have been marketed, little scientific information is available on whether or not they meet the various objectives. Reliable data on cost effectiveness are also not yet available.

11. More research is needed to develop models which accurately describe the changes in grain quality during the drying process in various dryer configurations. This information is necessary for the development of the next generation of automatic control systems.

12. Further research is also needed to develop new high-temperature dryer designs. These may involve completely different concepts (see Chapter 2) or may combine the optimum features of current designs (Hybrid dryers). Use of insulation to reduce heat loss from large commercial dryers has not been considered sufficiently, although some units are available with insulated plenums.

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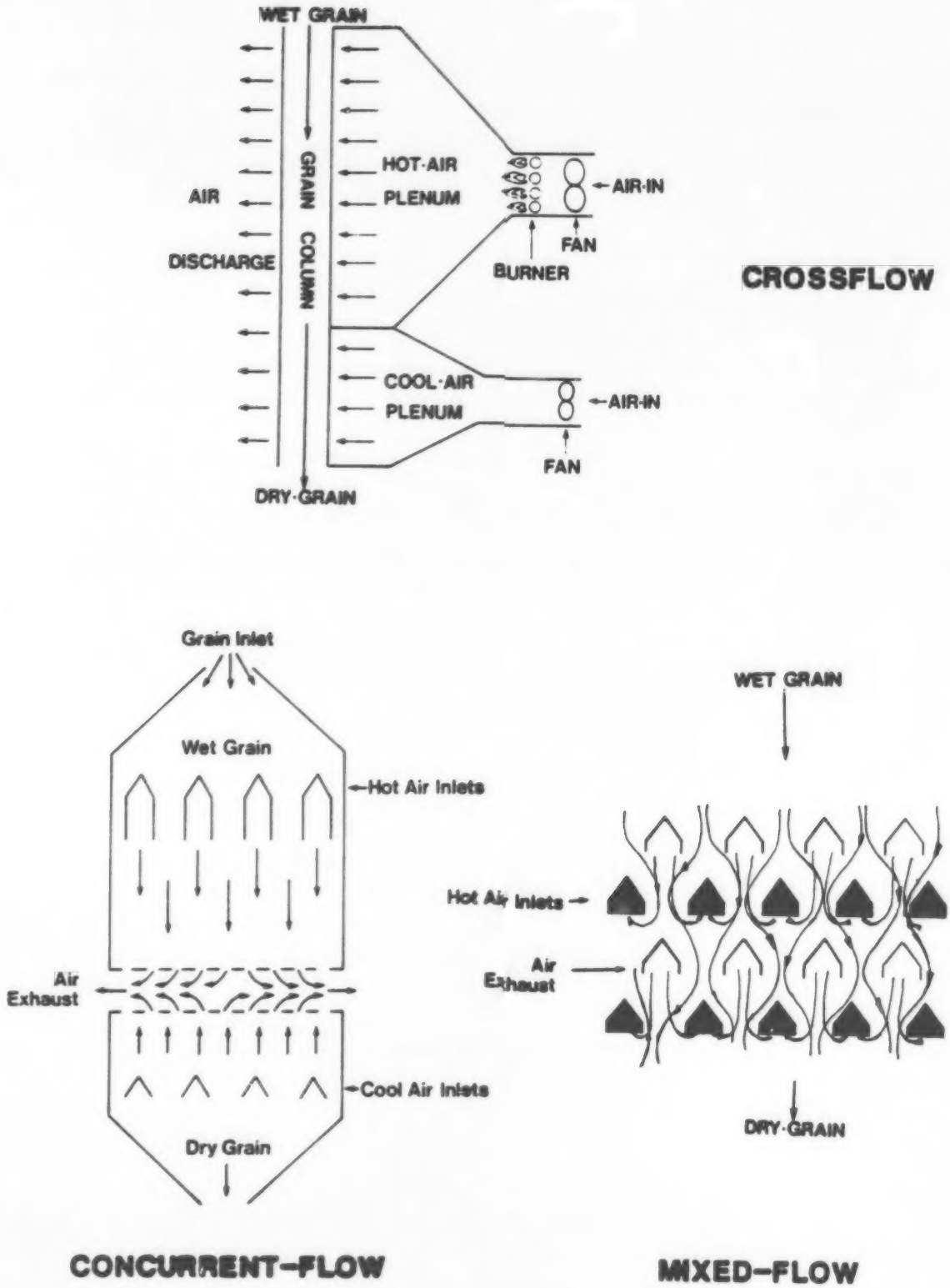

Figure 1.3.1 Some High-Temperature Dryer Configurations.

TABLE 1.3.1: SUMMARY OF FIELD TESTING OF HIGH-TEMPERATURE DRYERS

	Ambient temp. (°C)	Initial M.C. (% w.b.)	Final M.C. (% w.b.)	Drying air temp. (°C)	Airflow rate (m^3/m^2-hr)	Grain depth (cm)	Drying capacity (t/h)	Specific energy consumption (kJ/kg)	Reference	Comments
1. CROSS-FLOW DRYERS										
Adams batch recirculating	10	25.5	15.5	78	N/A	304 to 710	1.6	4400	Prahlich et al., 1984a	- artificially and naturally wet corn
Belt-O-Matic Model 320 continuous flow	3	32.5	14.6	116	2770	230	1.6	4693	Wallington Engineering Ltd., 1980	- cooling air and 1/3 to 1/2 of warm air was recycled
GTV380 batch recirculating	10	25.5	15.5	110	N/A	452	1.9	4100	Prahlich and Bartel, 1983b	- artificially and naturally wet corn controller
Belt-O-Matic 320 continuous flow	2	32.6	16.1	126	3060	150	2.0	4081	Wallington Engineering Ltd., 1980	- cooling air and 1/3 to 1/2 of warm air was recycled
Meridge Model 8400 recirculating batch	10	25.5	15.5	142	N/A	452	2.2	3700	Prahlich and Bartel 1983a	- artificially and naturally wet corn - drying cycle set by timer
Drymor redbird automatic batch	10	25.5	15.5	105	N/A	305	2.6	4200	Prahlich et al., 1984b	- artificially and naturally wet corn - airflow cycling ON/OFF at 15 second intervals
Super-B-AS-600G automatic batch	10	25.5	15.5	109	N/A	305	3.2	3600	Prahlich and Stock, 1985	- artificially and naturall wet corn - burner cycled ON/OFF for a preset part of a 15 second interval
Superb S500C continuous flow	10	25.5	15.5	97	N/A	drying 305 cooling 254	4.8	3500	Prahlich and Wassermann, 1982b	- artificially wetted corn - cooling and drying air recycling adjusted for initial moisture content
M-C665EM continuous flow	7	25.5	14.3	N/A	1660	305	5.1*	5486	Levesque et al., 1987 Shifflett, 1986	* manufacturer specification for corn from 25 to 15% moisture content - 25% drying air and 100 cooling air recirculated
Blount 1060 differential grain-speed continuous flow	19	23.6	13.8	108	1536	356	8.7	3831	Bakker-Arkema et al., 1982	- tapered columns, split dual grain-speed columns, two stage drying with grain mixing and tempering between drying stages and air-recycling of the cooling air

	Ambient temp. (°C)	Initial M.C. (% w.b.)	Final M.C. (% w.b.)	Drying air temp. (°C)	Airflow rate ($m^3/m^2 \cdot hr$)	Grain depth (mm)	Drying capacity (t/h)	Specific energy consumption (kJ/kg)	Reference	Comments
Hart-Carter MC-66 continuous flow	1	28.0	13.1	98	N/A	N/A	19.9	5000	Bakker-Arkema et al, 1981 Converse, 1972	- reverse airflow - portion of drying air and total cooling air recycling
Superb Optimum 6-100 continuous flow	-1	20.4	13.6	110	1254	305	25.0	4881	Moyes, 1977	- grain turning - reverse cooling airflow direction - adjustable plenum divider
Ferrell-Ross 4500 continuous flow	14	28.4	14.4	23-102	N/A	305	28.6	5799	Bauer and Walker, 1977 Bakker-Arkema et al., 1979	- air recirculation - six drying sections and two cooling sections - reverse airflow direction
Doreseve Welding Co. ACE four columns continuous flow	10.4	26.1	14.8	72	drying-1280 cooling-1600	300	37.9	5801	Otten et al., 1980	- grain inverter - reversed cooling airflow direction
Fallon 1500 continuous flow	2	26.0	14.5	95	1440	300	40*	4760	Ontario Research Foundation, 1986 Levesque et al., 1984	* nominal capacity for 10 percentage points removed from corn - 40% drying air and 100% cooling air recirculation
Ferrell-Ross 4500	7	24.4	15.1	102	drying-1344 cooling-1152	305	44.9	5056	Bakker-Arkema et al., 1979	- air recirculation - six drying sections and two cooling sections - reverse airflow direction
2. CONCURRENT-FLOW DRYERS										
Batch Internal Recycling Dryer (BIRD) Pilot Scale	10	21.7	14.9	316	drying-1829 cooling-627	heating-1500 steeping-3000 cooling-900	7.2	3864	Bakker-Arkema et al., 1981 Hall and Anderson, 1980	- grain recycled 8-9 times
Ferrell-Ross CCF 3-10-10 3 stage continuous flow	1	25.7	15.9	288 232 177	N/A	N/A	39.1	3724	Bakker-Arkema et al., 1981 Westelaken, 1977	
3. MIXED-FLOW DRYERS										
Vertec VT 5600 R continuous	10	25.5	15.5	97	N/A	762	5.3	4400	Prehlich and Wassermann, 1982a	- artificially wetted corn
Vertec VT 6600 continuous	8	25.6	15.6	90-100	N/A	762	6.4	4628	Laferrière et al., 1984	- 6 stages
Vertec VT 6600 continuous	9	25.0	17.0	107-143	N/A	762	9.9	4872	Laferrière et al., 1984	- air from the top six stages recirculated to the bottom six stages a the alternate side of t column.

2.0 NOVEL DRYING SYSTEMS

2.1 INTRODUCTION

Drying of wet materials is a common process in many industries and various methods of removing moisture have been developed. As mentioned in the previous section, either heated or ambient air drying is the most commonly used method in drying grains; however, other methods have been investigated in an attempt to reduce energy and improve quality. A few have been developed into commercial dryers.

One of the techniques involves the use of microwaves to supply the energy needed toe vaporate the moisture directly to the tunnel. Microwaves drying is used commercially in food and chemical processing and has been found to provide rapid, efficient drying with excellent control of product quality.

Another frequently used process to remove water from fluids and solids is desiccant drying. This process is based on the ability if certain materials to absorb large amounts of water. Since the absorption process is reversible, the desicants may be regenerated by either heating.

Conduction drying of wet materials is based on a rapid transfer of heat from a heated particulate medium to the wet solids. By intimately mixing both materials each wet particle is directly exposed to the heated paticles. The drying rate is usually rapid and the process efficient.

Drying of small solids may also be accomplished in a spouted or a fluidized bed. In either case heated air is used to provide the energy for drying, however, the high air velocities and temperatures and complete mixing of the solids result in high heat and mass transfer rates.

Although the above methods have been referred to as novel drying systems, they have been used in other industries and have all been considered for grain drying at some time in the past. Since the methods are not as well-known in the agricultural sector, each of them is described in terms of the basic concepts and a brief history of their agricultural use is provided.

2.2 MICROWAVE DRYING

2.2.1 INTRODUCTION

Microwave heating is a form of dielectric heating but refers to the heating that takes place in nonconductors due to polarization effects at frequencies between 300 MHz and 300 GHz or wavelengths between 1 m and 1 mm. Since microwaves are part of the electromagnetic spectrum, the U.S. Federal Communications Commission has allocated 13.56, 27.12, 40.68, 915, 2450, 5800 and 24225 MHz for industrial, scientific, and medical use. Other frequencies have been allocated in other countries; thus 42, 49, 56, 66, 84, 168, and 40.68 MHz are permitted in Great Britain. Austria, the Netherlands, Portugal, West Germany, Yugoslavia, and Switzerland allow 432.92 MHz. The Netherlands also permit 3390 and 6780 MHz. The Eastern Bloc countries use 2375 rather than 2450 MHz.

The vast majority of microwave ovens used in food processing employ 917 and 2450 MHz, with the latter one being the most popular frequency. Microwave heating at these frequencies result from interactions of the chemical constituents with the electromagnetic field. For example, water and other liquids with polar molecules will try to follow the rapidly changing polarity of the electromagnetic field. The resulting molecular agitation causes frictional heat which raises the temperature of the

material. If the temperature rise is large enough, the liquid molecules will evaporate rapidly.

It is well-known that in conventional heated air drying of grain there are four heat and mass transfer processes which may become responsible for limiting the drying rate. They are:

1. external heat transfer from the heated air to the outer surface of the grain kernel;
2. internal heat conduction from the surface to the evaporation front through the dried layer;
3. internal vapour diffusion from the evaporation front to the outer surface; and,
4. external vapour transfer from the surface of the grain kernel to the heated air.

These four rate limiting steps may occur individually or in series with one another. In most high-temperature grain dryers the effect of rate limiting steps 1 and 4 is minimized by using large volumes of heated air. This ensures a sufficient supply of energy for evaporation and removal of vapour without exceeding the maximum allowable grain temperature. However, as the grain becomes drier the energy and vapour must travel further to and from the evaporation front so that steps 2 and 3 become increasingly important.

There is little that can be done to improve the situation in conventional heated air dryers. However, if microwaves were used to supply the energy, both rate limiting steps 1 and 2 would be eliminated because microwaves penetrate the entire kernel and provide volumetric heating. Although the net result is more rapid drying, steps 3 and 4 remain.

Furthermore, if the energy transfer is too rapid the vapour may build up sufficient pressure to fracture the kernels. On the other hand, it has been claimed that careful control of the power levels may assist the diffusion of liquid water to the surface. In any microwave dryer moisture removal from the surface (step 4) will still require a moisture sink such as air. In some instances a vacuum is used to provide the sink, while in others it is a flow of air at ambient or increased temperatures.

2.2.2 EARLY WORK

The application of microwave energy to agricultural products include three main areas; namely, drying, control of insect infestation, and moisture content determination.

a) Drying

Early microwave grain drying research include the work of Hamid and Boulanger (1969). In an investigation aimed at the control of moisture and insect infestation, wheat was dried in two stages from an initial moisture content of 16.5 to 13.3% with 1.2 kW at a frequency of 2450 MHz. Boulanger et al. (1969) also considered the effect of airflow rates. Similarly, Fanslow and Saul (1971) dried field corn with microwave power and unheated air. They considered three sample sizes, three airflow rates through the microwave cavity, and three processing times. It was concluded that the market value of the corn was reduced due to swelling of the kernels after 3 minutes of exposure and that the airflow rates did not significantly affect the drying rates.

Experiments to determine the feasibility of microwave drying of grain corn was carried by Pei (1975), who is one of the foremost Canadian researcher in microwave technology. Three sets of experiments were carried

out. The first tests involved exposure of beds of corn of depths varying from 50 to 80 mm to microwave power at different levels of field strength and duration in a microwave oven. The drying process was observed to be slow at low field strength, while corn would 'pop' at high field strength. This led to the use of microwave power in a cyclic manner. A cycle consisting of 10 s "on" and 20 s "off" dried corn to 16% moisture content without popping. The second set of tests were carried out with a microwave conveyor-belt system, which had been developed for drying pasta. Corn at depths of 50 to 80 mm was placed on the perforated belt and exposed to microwaves at variable field strength as it moved back and forth inside the dryer. Corn was found to dry without popping in 600 s when the microwave power was maintained at 1 kW in each of the two generators. The third set of experiments also involved the microwave conveyor-belt dryer but with the grain corn placed in a rectangular casing. The casing had a perforated bottom to allow air to flow through the grain. In addition, the grain was preheated with hot air for about 5 minutes before the microwave power was turned on for 10 minutes. The process was completed with a 5-minute cooling step. As a result of the experimental work Pei proposed the construction of a dryer in which the grain made four passes, three drying passes with three 1 kW magnetrons per pass and one cooling pass. The moisture and warm exhaust air were to be collected and passed through a condenser before being used to preheat the wet grain entering the dryer. The design capacity of the prototype dryer was 380 kg wet corn.

In a subsequent project Pei (1985) retrofitted a commercial column dryer with a microwave power source. The objective was to assist the heated air system at the point where rate limiting steps 2 and 3 become dominant. However, the cooperator made a last minute decision not to modify the dryer

and the microwave unit was installed at the preheating level. Unfortunately this represents the least effective use of microwaves and therefore the results were disappointing.

b) Insect infestation

Since microwave heating can be used to kill bacteria, yeast and molds, it has been used to sterilize food products. For example, packaged bread and biscuits have been heated to about 75°C to kill molds and yeast, thus increasing the shelf-life by several weeks. The same principle can be used to kill insects and molds in grains (Hamid et al., 1968). In contrast with conventional air drying, microwaves provide volumetric heating of the material in the microwave field, and consequently insects are heated to fatal temperatures because of their high water content.

Of course, insect infestation or mold production during storage of agricultural products is also common. Depending upon the process, microwave power may be used to destroy the insects, molds and toxins. For example, Pei (1987) has developed equipment to sterilize and roast peanuts. However, except for high priced food commodities, the cost of microwave sterilization of grain is prohibitively high.

c) Moisture content determination

Standard methods of determining the moisture content of grains and seeds are time consuming and involve equipment and techniques not suitable for routine commercial use. For example, the air-oven methods require up to 72 h, while other basic tests such as toluene distillation and Karl Fisher titration require complicated equipment and intricate measurements. Since microwave drying is a rapid process, the use of microwave ovens to

determine the moisture content of samples of agricultural products has been investigated. Thus, Gorakhpurwalla et al. (1975) worked with corn and grain sorghum, Click and Baker (1980) with shelled corn, ear corn, soybeans, alfalfa, and potato chips, and Sverzut and Verma (1985) with shredded sugarcane. The results of these and various other investigations have led to the general conclusions that microwave ovens can indeed be used to determine the moisture content of agricultural products provided correct procedures are followed. The Ontario Ministry of Agriculture and Food has issued a factsheet outlining the procedure for determining the moisture content of alfalfa using a microwave oven (Bilanski and Ghate, 1978).

In addition to moisture content determination of grain samples, there is a need for continuous on-line measurements of moisture content to control drying or other processes. Some of the agricultural applications requiring moisture determination by non-destructive means have been reported by Nelson et al. (1953), Nelson (1965, 1973), Stetson and Nelson (1972), Busker (1968), Brain (1970), Kruse (1969), Phalen (1971). Grover (1971), Shah (1972), and Okabe et al. (1973), among others.

On-line methods involving microwaves are based on the fact that the amount of moisture in a material can be determined from the attenuation of microwave power through the material. In general, attenuation in grain obeys a linear relationship with moisture in the 10 GHz frequency range so that the methods provide good results over a limited range of moisture contents. Therefore, a number of microwave-based moisture sensors are available on the market.

2.2.3 MICROWAVE DRYERS

In the period of 1979 to 1982 a number of reports appeared in the

popular agricultural literature and newspapers dealing with the introduction of microwave dryers in the grain industry by two US companies. The McDonnell Douglas Corporation had designed and constructed the MIVAC system (McKinney et al., 1977) and Ken Bratney Company of Des Moines, Iowa produced the Vac-U-Wave dryer.

a) MIVAC system

According to Decareau (1985), a prototype unit of the MIVAC dryer was installed and tested at the U.S. Department of Agriculture's Southern Agricultural Energy Center in Tifton, Georgia. In this unit drying took place in a vertical cylindrical pressure vessel made of stainless steel. The 0.9 m diameter by 9.1 m cylinder was closed at the top and bottom by means of gasketed doors. A supply hopper at the upper end contained the wet product and a receiving hopper was located at the bottom. The actual drying zone was a chute between the hoppers. The chute was made of non-metallic, microwave-transparent material and had a large number of perforations along its length to allow water vapor to leave. The chute was placed inside a 457 x 457 mm wave guide through which microwaves at a frequency of 915 MHz provided the energy to evaporate the moisture. This frequency was selected to allow better penetration and distribution of the power. Outside the waveguide but inside the cylindrical vessel, was a condensing coil through which cold water circulated at a rate of 95 to 130 L/min. The vessel was evacuated so that vapour from the product would flow through the perforations in the chute and in the waveguide wall to the condensing coils. Condensate was removed from the bottom of the cylinder. Product flow was controlled with a valve at the bottom of the drying chute to 4.5 to 14 kg/min., which gave a residence time of about 30 min. The results of the

tests were reported to be satisfactory and energy savings of 40 to 62% were observed as compared with a heated air drying system.

Following the prototype tests, McDonnell Douglas Corporation in a joint operation with Aeroglide Corporation, a major grain dryer manufacturer, installed a 150 kW microwave vacuum dryer in a soybean plant owned by Continental Grain Co. of Guntersville, Alabama.

The 16.6 m high dryer was basically of the same design as the prototype unit except that three fibreglass chutes, each 0.6 m in diameter by 3 m long, were placed outside the centrally located waveguide. Each of three 50 kW microwave generators fed its energy into a waveguide at a frequency of 915 MHz, from which it was distributed to the wet product shutes through slots in the guide. According to Pei (1982), the location of the slots was unique and did not follow the traditional design of varying the slot size at fixed spacing. Instead, the slots were oriented with respect to each other to obtain a uniformily outward radiating microwave field along the entire length of each of the three guides. A vacuum system kept the cylindrical vessel at an operating pressure in the range of 3.4 to 6.6 kPa. Nominal capacity of the unit was determined to be 5.9 m^3 of soybeans/h at a moisture removal of 2%. For this particular application the major objective of using microwaves and a vacuum system was gentle rupturing of the outer skin of the bean, thus preconditioning it for further processing.

b) Vac-U-Wave Dryer

Instead of using costly high power magnetrons to generate the microwave energy, the Vac-U-Wave design was based on using a large number of 1.2 kW magnetrons which are mass produced for kitchen microwave ovens. Depending upon the capacity, the dryer used 18, 36 or 54 magnetrons to provide 25, 50

or 75 kW of microwave power, respectively. The drying chamber consisted of a horizontal trough with a double-bladed auger (two primary and two secondary flights). Pei (1982) explained that the two blades formed a cavity in which the grain was exposed to microwaves at each individual waveguide opening. This design allowed very little microwave leakage along the trough, thus eliminating interference among the equally spaced magnetrons.

Wet product was fed from a hopper through a preheating section and an inlet rotary air-lock feeder to the two primary drying troughs. A set of secondary drying troughs were located below the primary ones. Grains passed through both sets of troughs before being discharged uncooled via the outlet rotary air lock. Moisture released by the grain was removed from the troughs with a vacuum system operating at 30 to 50 kPa. The vapour was used in an air-to-air heat exchanger to preheat the wet grain. Heated air was also obtained from the the magnetron cooling system and used to preheat the wet grain. The dryer was obviously designed to maximize energy use and the company claimed energy consumption to be "well below 1160 kJ/kg of water removed".

In response to requests by farmers and elevator operators, Otten attempted to obtain the experimental data on which the energy and capacity claims were based. However, the company did not produce the information but the company's vice-president repeated the 1160 kJ/kg claim in a letter (Alles, 1982).

Pei (1982) also attempted to obtain specific data on the dryer and visited the manufacturer. He learned that the observed results were actually of the order of 1600 to 1860 kJ/kg and that they included a 2% moisture loss during cooling of the warm grain in a storage bin (dryeration). Using advertising data provided by the company for Model VUW

2420, Pei calculated that with an electrical energy input of about 200 kW the maximum amount of moisture removed would be 2% points rather than the 5% claimed by the manufacturer. He also pointed out that if the efficiency of converting electrical energy into heat via microwaves, which is from 15 to 50%, were taken into account, the drying capacity would be much smaller.

c) Current Status

At present neither of the two dryers is commercially available for grain drying. Development work is continuing on the MIVAC dryer but much of it is directed towards non-agricultural applications. However, in addition to smaller laboratory dryers, one of which is in use at the University of Saskatchewan, the McDonnell Douglas Corporation expects to build a large agricultural dryer in cooperation with a major dryer manufacturer (probably Aero- glide Corporation) by the third quarter of 1987 (Ware, 1987). The company would not release any further details, not even the product to be dried; however, it appears that most of the technical problems have been solved and that the preliminary economic evaluation was sufficiently promising to start a market study.

The Vac-U-Wave dryer was made commercially available in 1982 but the dryer did not perform as advertised. The Ken Bratney Company seemed to have recalled the few dryers sold but was unable to solve the performance problems. The dryer design was sold to the Waconia Manufacturing Co., Waconia, Minnesota. Smaller dryer units have been used to dry such chemicals as poly-styrene resins and an agreement seems to have been reached with Conair of Franklin, Pennsylvania to build another dryer for agricultural use (Moses, 1987). No further details were released by either company but it appears that the main obstacle is that the dryer cannot compete economically

with conventional heated air drying of bulk grain.

d) Safety and electric demand considerations

The design of any microwave dryer must consider radiation leakage. Fortunately microwaves are in the same category as radio-, light-, and infrared waves. These produce non-ionizing radiation, which means that their effect is only a thermal one; that is, the interaction of the radiation with materials will result in a temperature increase if the radiation intensity is high enough. Subsequent changes in the material will then only be due to the temperature rise. Since water in the human body readily absorbs microwave radiation, the temperature rise would serve as a warning and allow the operator to move away from the equipment in case of excessive leakage. In contrast, such radiation as X-rays, UV-rays, and cosmic rays produce ionizing radiation, which may result in chemical changes in matter without a temperature rise. Their effect is not observed until it is too late. Nevertheless, according government standards microwave leakage from an oven cannot exceed 1 mW/cm^2 when measured 5 cm from the oven. Measurement of such levels of radiation is difficult and requires specialized and expensive equipment operated by experts. Even if the dryer were designed to meet the leakage constraints, there remains the problem of maintaining the standards during routine farm use of the dryer. The farmer cannot make the temporary repairs commonly found in other grain drying systems.

Microwave dryers are basically a form of electric dryers in that they ulitize electrical energy rather than fuels. Although microwave dryers appear to be more efficient than heated air dryers, the electric power demand is high and the farmer will run into a demand charge if he exceeds

the basic 50 kW. The cost of drying would then increase dramatically.

2.2.4 SUMMARY

1. Microwave drying is faster than heated air drying because it provides volumetric heating, thus eliminating some of the rate limiting steps.

2. Experimental results have demonstrated that microwave drying is more energy efficient than heated air drying and results in a high quality product.

3. At present no commercial microwave dryer is available for drying of large quantities of grain; a few smaller units have been used for special applications.

4. At least two U.S. companies are continuing with the development of microwave dryers for agricultural products but economic constraints may restrict their use to the drying or processing of special crops.

5. Additional research is required to discover the design parameters and operating conditions to make microwave drying of agricultural products profitable.

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2.3 DESICCANT DRYING

2.3.1 INTRODUCTION

Desiccant drying systems can be divided into two groups; one in which the air used to dry the wet product is first dehumidified by passing it through a desiccant bed and one in which the wet product is mixed with a desiccant and allowed to come to an equilibrium moisture content.

Dehumidification of gases, including air, is a common industrial process and often involves a bed of desiccant material. Examples include dehumidifiers for electronic, electrical equipment and optical equipment, and warehouse and ship holds dehumidifiers.

The phenomena on which dehumidifiers operate is adsorption and desorption. During adsorption specific gas or vapor molecules interact with the solid adsorbent and concentrate at the interphase, thus reducing the concentration of the species in the gas phase. The process is a spontaneous one and as such it is accompanied by a decrease in the free energy of the system. Once the desiccant bed has been saturated or the exit concentration of the species exceeds a given value, the adsorbent is regenerated before being used again. The physically adsorbed molecules can be removed at a reduced pressure at the same temperature where the adsorption took place or at an elevated temperature. The specific regeneration conditions depend upon the type of adsorbent and the desired rate of regeneration.

2.3.2 SILICA GEL

One of the earliest attempts to use a desiccant to dry grain corn was by Danziger et al. (1972). In one set of experiments corn-silica gel mixtures were sealed in pint Mason jars and the moisture exchange between the two materials was recorded. In a separate experiment air was dehydrated

in a silica gel bed before flowing upward through the corn bed in a closed loop system. All experiments were conducted at room temperature.

In the static drying experiments a mixture of 0.33 g of silica gel per gram of wet corn dried the corn from 24.9 to 14.6% (w.b.) within 24h. Varying the ratio of silica gel to corn from 0.1 to 0.35 showed that the equilibrium moisture content obtained in 48h varied from 22 to 14% (w.b.), respectively. Ash content tests on the corn samples after separating the materials showed that silica gel particles did not adhere to the corn.

The closed air circulation experiments involved both single batch and layered batch drying. In both cases it was discovered that a significant moisture profile was present when the average moisture content had reached the desired level. For example, when 1.4 kg of 26.5% corn was dried, the average moisture content after 24 h was 15.0% but the bottom layer had dried to 5% and the top surface was still at 26.5% (w.b.).

Germination tests showed germination rates above 90% for both types of drying experiments, which is the same as that of undried corn. Hence, room drying with silica gel produced excellent grain quality. No information was obtained on the energy requirements of regenerating the silica gel.

A direct application of an industrial dehumidifier to condition the drying air was investigated by Rodda and Rode (1977) and Rodda (1979). In the first study 75% of the air leaving the laboratory dryer was passed through a rotary dehumidifier and blown over the cooling coils of a window type air conditioner to limit the temperature rise due to heat gain from the latent heat of condensation. The heat rejected from the air conditioner was used to preheat the regeneration airstream. In drying shallow beds (0.6 m) of soybeans using airflow rates of 5.7 m^3/min, it was observed that the

regeneration energy requirements were about 5800 kJ/kg of water removed for a total energy consumption of 7100 kJ/kg. Hence, the regeneration process accounted for 82% of the energy consumption.

The authors compared their results with data obtained from a seed corn plant where 69.5 m^3/s of ambient air was mixed with 47.2 m^3/s of dry air supplied by two dehumidifiers. Data for 1976 also showed an energy requirement of 6950 kJ/kg of water removed. In discussing the results the authors indicated that the energy use should drop to 4200 kJ/kg if ambient air was used to fully utilize the heat of adsorption directly for moisture removal.

In the second study by Rodda (1979) the air conditioner was eliminated and an air-to-air heat exchanger added. The exchanger was used to extract heat from the exhaust air of the regeneration sector of the dehumidifier to preheat the ambient air used to dry the desiccant. This arrangement reduced the regeneration energy required to 3900 kJ/kg of water removed and the total energy to 5900 kJ/kg. The quality of the corn was again excellent because drying was done below 40°C.

Farouk et al. (1981) considered the effect of dust on the sorption properties of silice gel, activated aluminum and a molecular sieve. Inorganic dust particles wit a diameter of 10 to 20 micrometers were mixed with the desicant material to from a 0 to 5% mixture by weight. The addition of dust did not affect the equilibrium moisture content of te desicants but reduced the dynamic moisutre sorption rate of all three materials. For example, the absorption rate were decreased by 50% by the presence of 5% dust when the desiccants were aerated with 70% relative humidity air flowing at 0.4 $m^3/s.m^2$.

2.3.3 SOLAR REGENERATION OF SILICA GEL

Because the regeneration process accounted for the major portion of the total energy requirement, the use of solar energy to dry desiccants was considered by a number of researchers. For example, Koh et al. (1978) designed a flat-plate collector and found that a 3 m^2 collector was capable of regenerating shallow beds of silica gel from an initial moisture content of about 29% to 3% (d.b.) in 2 to 7 days, depending upon the bed depth and insolation. Since the beds were 800 mm in diameter and the depths varied from 27 to 89 mm, the amount of regenerated silica gel was only 0.04 to 0.12 m^3. The collector and thermal efficiencies were calculated to be about 50%.

Tomlinson and Miller (1981), who were interested in drying of fresh citrus fruit, investigated regeneration of silica gel by direct exposure to solar radiation rather than by using solar heated air. They placed silica gel on the absorber plate of a covered solar collector and passed air over the gel to increase the evaporation rate. Tests were run with collector loadings of 18.1, 22.7 and 27.2 kg of silica gel for an individual collector area of 2.2 m^2. Desiccant thicknesses of 12, 16 and 20 mm and airflow rates of 0.0042 and 0.0190 m^3/s were used. Under those conditions 29% (d.b.) silica gel was dried to 7 and 10% in about two days in February and March in Florida. The authors also presented a mathematical model to describe the regeneration process. Although they concluded that direct solar regeneration was technically feasible and a more efficient use of solar energy than indirect solar regeneration, the amounts of silica gel were small and the beds shallow; in addition, the tests were run at solar radiation levels of about 600 W/m^2.

More recently, Miller (1985) described a system in which hot air collectors were coupled with a desiccant storage to surface dry fresh

produce. Heated air from the flat plate collectors was used to either directly surface dry fruit or regenerate activated alumina or silica gel. During periods of low solar radiation, ambient air was dehumidified by the desiccant before being used to dry the fruit. Low efficiencies of regeneration of the 760 kg of alumina and 710 kg of silica gel beds led to the conclusion that the main justification for the desiccant unit would be as an emergency system when fossil fuel was not available.

Aldis et al. (1980) conditioned silica gel by drying it for two days with air heated in the collectors designed by Koh (1977). A 1250 kg batch of 23.5% (w.b.) corn was dried with a 40:60 mixture of ambient and desiccant air until the surface of the 0.66 m deep bed was 15%. The process took 280 h as compared with 350 h for a duplicate batch dried with ambient air alone. Mold counts and aflatoxin concentrations were significantly lower in the first batch but the susceptibility to breakage was the same. The energy use was measured to be 360 kJ/kg of water removed for the desiccant dried batch and 320 kJ/kg for the ambient one. These values are an order of magnitude lower than Rodda's results (1979). In another experiment two 1250 kg batches of milo with an initial moisture content of 18.5% (w.b.) were dried in 0.53 m deep beds. The 60:40 mixture of ambient to desiccant air dried the batch in 210 h and the ambient air alone required 330 h. In this case the energy use analysis showed that the desiccant assisted system used 0.65 MJ/kg of water removed and the ambient one 790 kJ/kg.

Pressure drop measurements made by Aldis et al. (1980) of a loosely filled bed of silica gel showed variations from 0.8 to 5.0 kPa at airflow rates of 0.07 to 0.37 $m^3/s.m^2$ of bed at bed depths of 0.3, 0.6 and 0.9 m. After compacting the bed it was found that the increase in pressure drop was about

0.2 kPa/m of silica gel at an airflow rate of 0.077 $m^3/s.m^2$ of bed.

2.3.4 BENTONITE

Although silica gel has excellent properties as a desiccant and is often selected for industrial applications, it is relatively expensive. Therefore, bentonite has been considered as an alternative desiccant for grain drying (Sturton et al., 1981; Graham et al., 1983; Watts et al., 1986; Watts and Bilanski, 1987). The first two references deal with experimental work in which freshly harvested grain was mixed with bentonite in 150 L plastic barrels. Thus, it was demonstrated that a 1:1 grain mass to bentonite mass ratio dried wheat from 15% to 11.8% (w.b.) and oats from 22% to 14.5% (w.b.) in 24 and 28 h, respectively. Similarly, a ratio of 1 kg of wet corn (29.4%) to 2 kg of bentonite (8.2% m.c.) dried corn to 18.7% in 23 h and to 15.5% in 171 h. It is clear from these results that the initial drying rate is high when the materials are mixed. After drying the mixtures were separated by passing them through a fan mill. No information was provided on the separation process but it was mentioned that since bentonite is a common food and feed additive, small amounts of bentonite which might adhere to the grain should not be harmful. No results were reported on the regeneration of bentonite so that no energy data were supplied.

Graham et al. (1983) continued the work with bentonite. It was shown again that a 1:1 wet grain mass to dry bentonite mass resulted in a rapid drying of the grain. For example, corn with an initial moisture content of 30% (w.b.) dried to 17.5% in 24 h when mixed with 0.5% (m.c.) bentonite. Similar observations were made for wheat and oats.

Watts et al. (1986) compared calcium-based with sodium-based bentonite in drying grain corn. It was concluded that the former adsorbed more

moisture and is therefore preferable for drying applications. In addition, the authors showed that it was possible to predict the experimental observations using existing drying and equilibrium moisture relationship for corn. In a subsequent paper Watts and Bilanski (1987) described a model to simulate the adsorption drying of corn, wheat, barley and oats using sodium bentonite.

Although it was stated in some of the publications that bentonite could be regenerated with low grade solar energy, no results were presented to verify this.

2.3.5 OVERDRIED CORN

A somewhat different approach to dessicant drying of wet corn was looked at in 1977 and 1978 by Bern et al. (1979). In the two year study a conventional low-temperature drying system was compared with a combination desiccant/low-temperature process. The interesting aspect of the experiments was that the desiccant was overdried corn. During each summer about 20 t of dry, clean corn was placed in a 5.5 m diameter drying bin which received heated air from a 17.8 m^2 solar field. By setting the controls to ensure favorable drying conditions, the grain was dried to 11.7% and 8.9% (w.b.) in 1977 and 1978, respectively. The conditioning period was from August 1 to September 20 in 1977 and from June 7 to September 22 in 1978, during which the drying fan ran 112 and 537 h, respectively. In the second week of October wet corn was placed on the desiccant corn and mixed with a single-auger, grain stirrer. In 1977, 21 t of desiccant corn and 59 t of 23.3% m.c. corn was mixed and in 1978, 15 t of desiccant corn was mixed with 61 t of 22.8% corn. The results indicated that the total energy use for the combination system was much less than for the conventional low-temperature

one (2100 versus 5000 kJ/t.% moisture) in 1977 and 14 versus 3400 kJ/t.% moisture in 1978). It was also shown that desiccant corn preparation was an energy efficient process at 558 kJ of fan energy per kg of water removed.

A cost comparison of the two systems showed the desiccant one to cost about 60% more per unit of drying capacity than the conventional system (annual net cost per tonne capacity: $14.03 versus $8.92). The higher cost was due to the need to purchase a stirrer, solar collector and desiccant corn and to the reduction in dryer capacity.

In a separate experiment Nguyen et al. (1984) considered the effect of drying, wetting and redrying of the desiccant corn on grain quality. Stein breakage tests indicated a significant increase in susceptibility to breakage; however, it was concluded that normal handling of corn during the desiccant drying process would only result in a breakage of 0.1 to 1.7%.

Anderson et al. (1984) presented a simulation model to describe summer preparation of desiccant corn using heat from solar collectors. Based on the simulation results they recommended an airflow rate of 0.014 $m^3/s.t$ along with a grain mass to collectorarea ratio between 3 and 5.5 t/m^2. These conditions will result in a desiccant corn with a moisture content of 8 to 10% with an acceptable collector size and electrical energy input.

2.3.6 LIQUID DESICCANTS

All of the above desiccants are examples of insoluble solid desiccants. In addition to these there are soluble liquid and soluble solid desiccants. Liquid desiccants include deliquescent salt solutions such as lithium and sodiudm chloride in water as well as organic compounds like glycerol and sulphuric acid. One of the main advantages of liquid desiccants in the ease of handling, especially in solar regeneration systems. In these cases the

dilute desiccant solution can be used directly as the collector fluid, thus optimizing the heat transfer in the solar system.

Ko et al. (1977) performed a feasibility study to determine the suitability of lithium chloride as a liquid desiccant in a crop drying system. The presented the conceptual designs of batch and continuous flow drying systems in which the desiccant was regenerated with solar energy or a backup resistance heater. The systems were relatively complex involving stripping and absorption columns, various heat exchangers, and a solar energy consumption of the order of 2400 kJ/kg of water removed, which the authors considered to be a savings of about 50% over conventional high temperature drying. The obviously high capital cost was not mentioned.

2.3.7 SUMMARY

1. Desiccant drying of grain with dehumidified air or using intimate mixtures is technically possible. Dehumidified air drying, especially when a mixture of ambient and dehumidified air is used, is a modified version of low temperature drying and the drying periods are long. In contrast, the method of mixtures causes more rapid drying.

2. The grain quality is generally excellent and is a direct result of the low temperatures at which the grain is dried.

3. There is insufficient information on the energy requirements but the indication is that the total energy use is comparable with conventional high temperature drying.

4. Limited cost data indicates that desiccant drying systems are more costly than low temperature drying with ambient air because of the need to purchase and store desiccant, solar collectors or equivalent regeneration equipment, and separators.

5. Regeneration studies have been done on a small scale. To dry large quantities of desiccant large collector areas and high volume/high pressure air movement equipment are needed. Additional labour cost must also be considered.

6. The cost of desiccants is high; for example, silica gel is $ 4000/t, bentonite is $ 150/t. To dry 100 t of wet corn using a 1:1 mass ratio requires $ 15,000 worth of bentonite. The interest alone at 10% is $ 15/t and is higher than the $ 13/t charged for custom drying of 27% corn. (Lowest priced silica gel was quoted at $4/kg by in barrel lots by Standard Chemicals)

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2.4 SOLID-SOLID CONTACT DRYING

2.4.1 INTRODUCTION

In a solid-solid medium or particulate medium drying system the wet product is mixed with a heated granular material, such as sand, salt or glass beads. It is different from desiccant drying in that the granular medium does not adsorb the moisture but supplies the thermal energy for evaporation of the moisture. Heat transfer from the medium to the grain takes place mainly by conduction. The evaporated moisture is then removed with air.

Rapid drying may be achieved by increasing the heat transfer rates through continuous mixing and agitation of the mixture. Research has shown that the drying or residence times of grains is of the order of minutes rather than hours as in conventional high temperature dryers. Furthermore, thermal efficiencies of 60% or higher are possible. Once the desired moisture loss has been obtained, the grain is separated from the particulate medium through sieving. Although much of the reseach was done on batch systems, the process can be designed to operate on a continuous basis.

An excellent review of particulate medium drying was presented by Richard and Raghavan (1984). Some of the following information was taken from this source and other material provided by Raghavan (1986).

Conduction drying of grain using particulate mixtures can be viewed as being an improved version of conduction drying of grain in contact with a heated surface,as studied by Hall and Hall (1961) and Finney et al. (1963). Thin layers of corn placed on a steel plate suspended above an electric hot plate were found to dry about 10% faster than convection drying. It was also shown that moisture removal was mainly from the tip of the kernels. Gerzhoi and Samochetov (1961) dried grain by contact with the outer surface of

heated pipes, while Chancellor (1968a, 1968b) dried mechanically stirred rice by placing it on a heated horizontal surface. He tested a 2.4 and a 4.8 m diameter dryer in which rice straw was used as the fuel. His work was aimed at developing a simple rice drying system for tropical areas.

Each of the researchers had problems with nonuniform drying caused by a lack of temperature control. Although Hall and Hall (1961) suggested mixing of an inert heated material with the grain to provide heat by conduction, they did not pursue the idea. However, drying and roasting of grain by mixing it with heated sand has been used in parts of Africa and India for a long time. For example, Richard and Raghavan (1984) pointed out that Sethi *et al.* (1937) used hot sand in heating soaked paddy as a part of the parboiling process.

2.4.2 GRANULAR MEDIA

Akpaetok (1973) constructed a rotary laboratory dryer in which heated sand and wet corn were mixed. The drying time was determined by the angular velocity and the angle of inclination of the drum. Tests were run with sand temperatures of 150 to 200 °C and drying times of 100 to 300 s. Suitable combinations of these conditions resulted in drying corn from an initial moisture content of 25 to a final content of 18.5% (w.b.).

Raghavan *et al.* (1974) suggested using heated granular salt as a heat transfer medium to obtain high heat transfer rates in a continuous drying process. Hence, Raghavan and Harper (1974) conducted experiments using a rotary drum (610 mm dia. x 760 mm long) similar to the one used by Benson (1966) to puff cooked cereal with heated salt. Although the equipment was tested using salt temperatures of 200 to 275 °C and residence times of 4 to 20 s to dry corn from 21 to 12% (w.b.), the optimum conditions for the

production of corn of feed quality was a salt bed temperature of 230 °C and a residence time of 13 to 20 s. The wet corn feed rate ranged from 300 to 700 kg/h.

In a recent study Raghavan and Alikhani (1986) compared the use of molecular sieves to sand in drying corn in an eccentrically rotating cylinder designed for batch processing. It was concluded that molecular sieves were superior to sand with the greatest advantage being at higher residence times.

Lapp (1973) investigated the use of heated sand and steel balls in drying of rapeseed. Since the preliminary tests showed that the process was feasible, a continuous flow dryer was designed by Lapp and Manchur (1974). The dryer was found to reduce the moisture content of rapeseed with an initial moisture content of 14% by 3.7 to 5.8% points using a sand to rapeseed ratio of 3:1. The corresponding drying efficiency was determined to be 65% and the residence time about 30 s.

In subsequent work Lapp et al. (1975, 1976) dried wheat from 17.0 to 14.5% moisture content in 120 s using sand heated to 100 °C and a sand-to-wheat weight ratio of 4:1. Sand heated to 105 °C and a ratio of 4.5:1 dried wheat in just 60 s, without reducing the baking quality of the flour. In further work with the unit Lapp et al. (1977) and Mittal et al. (1982, 1983, 1985) examined sand to wheat ratios of 4:1, 4.5:1 and 5:1 and grain flow rates of 1.5 to 6.0 kg/min., in steps of 0.5 kg/min. The maximum moisture removal occured at a ratio of 4.5:1, a grain mass flow rate of 3.0 kg/min. and a sand temperature of 105 °C. The drying and fuel efficiencies were also determined. An average drying efficiency of 61.2% was obtained for grain flow rates ranging from 2.5 to 3.5 kg/min at a sand to grain mass ratio of

4:1. A maxium fuel efficiency of 40.7% corresponded to a grain flow rate of 3.0 kg/min and a sand-to-grain mass ratio of 4:1. The specific energy consumption varied from 6.34 MJ/ kg of water removed, while this minimum value was found at a grain flow rate of 3.0 kg/min. and a mass ratio of 4:1.

Another approach to obtain continuous mixing of the grain-particulate mixture was investigated by Savoie and Desilets (1978). They used a fluidized bed of corn and heated sand. Some problems were encountered in controlling the residence time but it was shown that under certain conditions, fluidization of the mixture was possible and that mixing was almost perfect. The drying efficiency was reported to vary from 18 to 59%.

It was pointed out by Richard and Raghavan (1984) that conduction drying using a particulate medium depended upon a number of process parameters. In order to illustrate this, they summarized the performance information obtained by various researchers, including those presented above. The summary, which is found in Table 2.4.1, shows that there is considerable variation in the grain-to-medium mass ratio, amount of moisture removed, temperature of the medium and the residence time of the grain in the dryer. In fact, in the case of corn drying with heated sand, the sand-to-corn mass ratio was shown to vary from 2:1 to 9.6:1, the sand temperature from 76 to 204 ^{o}C, and the residence time from 78 to 1008 s. The authors believed that the lack of data and understanding of the process fundamentals were the main reasons that no commercial dryer had evolved from the research in the seventies.

Recently, Simonton and Stone (1986a) considered the performance characteristics of a counterflow particle-to-particle heat exchanger with dual heating and heat recovery stages. In a number of laboratory tests 0.45 kg of wheat and 0.9 to 2.3 kg of heated table salt or Norton-Alcove

Interprop heat transfer material were poured simultaneously into a calorimeter to determine the heat transfer coefficient. The results were used to simulate the effects of medium-to-grain mass rates, medium-to-grain heat capacity, heat exchanger length, and outlet which temperature on energy input to operate the heat exchanger. It was predicted that a 41% savings in energy was possible with the exchanger when compared with a conventional dryer.

Based on the simulation results Simonton and Stone (1986b) designed, built and tested a prototype counterflow particle-to-particle heat exchanger. After considering various mechanical configurations, a mechanism involving gravity-induced flow over an inclined screen was selected for the separation section of the cell unit. The dryer consisted of a two-stage particle-to-particle heat exchanger with five cells for stage all of which are related as a low angular velocity. Mixing and separation of the wet products and the granular heat transfer medium takes place in the cell such that the product flow is opposite to the medium flow. A number of tests were conducted with wheat and salt or wheat and Norton-Alcon Interprop heat transfer material at different rates of energy input and rotational speeds. The salt tests showed that the average thermal efficiency was 67.2% at 1 rpm, while Interprop averaged 53.4%. In addition, a peak thermal efficiency of 84% observed at 1.45 rmp. However, one information was provided as the drying characteristics of the unit.

2.4.3 COMMERCIAL DRYER DEVELOPMENT

Following the initial success by Raghavan and Harper (1974), the dryer redesigned to allow recirculation of sand along the entire 1.8 m length of the 0.70 m drum. A set of helixes controlled the residence time of the grain

in the drum and the degree of mixing. In testing the dryer Tessier and Raghavan (1984) varied the wet corn feed rate from 5 to 12 kg/min. and the residence time from 18 to 29 s. The average moisture removal from corn with an initial moisture content of about 36% (d.b.) was 3.4 percentage points (d.b.) with sand at 150 °C. The calculated drying efficiency ranged from 25 to 39%, whereas the fuel efficiency was 60 to 95%.

Further design work resulted in a dryer for which US Patents were issued in July, 1985 (Raghavan and Pannu, 1985). The unit was described by Pannu and Raghavan (1985, 1987) to consist of three conical sections: an inside-conical-drum for heating the particulate medium, an outer-conical-drum for mixing of the heated grain and transporting of the mixture to the separation section, and the last-conical drum for collecting and recirculating the medium. A 44 kW propane burner protruded into the inside-conical-drum while buckets attached to the inside wall of the drum directed the medium particles several times throught the hot section of the flame. Wet grain is mixed with the heated drying medium in the annular space between the inside- and outside-conical-drums. The mixture is retained in this space to ensure sufficient contact time before being separated (Figure 2.4.1). The dryer performance was evaluated to determine the energy use, drying capacity, residence time and moisture loss. Wet corn feed rates of 0.24 to 0.52 t/h were used at various grain moisture contents, sand temperatures and grain residence times. The separation process was found to be complete and the sand recirculation good at angular velocities of 1.6 to 2.6 rad/s. At high grain mass flow rates and contact times of 12.2 to 19.3 s the moisture loss varied from 1.25 to 5.32 percentage points (w.b), which was considered to compare favourably with other studies. The average

moisture removal from corn with an initial moisture content of 30% (w.b) was 3 to 4% points. The drying efficiency ranged betwen 11 and 26% and the heating efficiency between 69 and 90%. Because the grain was discharged at an average temperature of 80 to 90°C, it was suggested that the sensible heat be used to evaporate additional moisture by using an efficient aeration unit attached to the dryer.

It appears that all the experiments reported in the paper were single passes of wet corn; however, since only 3 to 4% points were removed in the first pass, 30% corn would have to make 4 or more passes before a suitable storage moisture content is obtained. Since moisture diffusion from inside the kernel is slower than surface moisture loss, each pass will remove correspondingly less moisture at the same residence time. The result is a much lower dryer capacity lower efficiency than reported. It would appear that the equipment should include a steeping system to allow moisture diffusion and removal between successive passes.

2.4.4 COMMERCIAL DRYER FUTURE

The particulate dryer has been licensed to Ventilateur Victoria Ltee of Victoriaville through CRIQ (Centre de Recherche Industrielle du Quebec) for manufacturing. However, further development work will include (Raghavan, 1986):

i) an evaluation of zeolites to improve the drying efficiency;

ii) burner modifications to improve heating efficiency;

iii) flue gas removal improvement;

iv) long term performance studies with freshly harvested corn; and

v) quantification of the mass transfer aspects.

It is expected that further development of the dryer will be of the

order of $ 500,000.

2.4.5 SUMMARY

1. The results of various studies indicate that particulate medium drying of grains and oilseeds is technically feasible and results in high drying rates.

2. The conduction drying process is a function of various parameters, with the main ones being the initial grain moisture content, initial medium temperature, type of medium, medium particle size, medium to grain mass ratio, and contact time. Not enough data are available to describe the relationship for various dryers.

3. Further tests are needed to determine the long term capacity and efficiency of the commercial prototype dryer; however, Raghavan (1986) believes that the drying efficiency will be significantly higher than that of a conventional cross flow dryer and estimated that the cost/benefit ratio for the new dryer will be about 30% of that of the conventional methods.

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TABLE 2.4.1: SUMMARY OF SOLID MEDIUM DRYER DATA. (Richard and Raghavan, 1984)

Material dried	Medium used	Initial M.C., % w.b.	Final M.C., % w.b.	Material to medium ratio weight	Inital medium temperature °C	Residence time, s	Drying efficiency %	Ref.
Corn	Salt	20.92	11.95	1:20	260	20		Raghavan and Harper (1974)
		20.92	15.09	1:20	204	13		
		20.92	14.96	1:20	204	4.2		
		20.92	12.99	1:20	275	13		
Corn	Salt	15.3	10.0	1:20	274	30		Mayfield (1974)
		15.3	11.9	1:20	232	30		
Corn[a]	Sand	25.0	18.29	1:5	204	300	Up to 60%	Akpaetok (1973)
		25.0	21.02	1:5	154	300		
		25.0	22.7	1:5	98	300		
Corn[b]	Sand	24.9	18.73	1:2[c]	87	100		
		14.62	14.14	1:2[c]	76	78		
Rapeseed	Sand	12.0	9.8	1:1.5	163	30	56.5	Lapp and Marchur (1974)
		14.0	9.5	1:2.25	221	30	49.9	
		12.5	9.1	1:3	168	30	48.1	
Rapeseed	Sand	13.5	10.2	1:2	135	30	85.2	Marchur (1973)
		15.0	10.8	1:2	170	30	75.9	
		15.0	11.3	1:3	130	30	68.0	
		15.0	9.2	1:3	190	30	70.0	
Wild rice	Sand	57.98	12.23	1:16	250	300		Lapp et al. (1976)
		71.31	3.76	1:24	250	600		
		56.39	27.13	1:24	150	900		
Wheat	Sand	16.8	14.4	1:4	105	60	62.2	
		17.1	14.65	1:4.5	104	60	62.0	
		17.3	14.92	1:5	105	60	60.2	
Wheat	Salt Steel	17.2[d] (avg.)	15.2[e] 15.45[e]	1:4 1:4	100 100	120 120	45 62	
Corn	Sand	21.69	18.57	1:8.7	89[f] (avg)	1008	Up to 59%[g]	Savoie and Desilets (1978)
		21.88	19.74	1:9.6		477		
		29.38	26.95	1:4.5		288		

[a]Batch dryer.
[b]Continuous flow dryer.
[c]Calculated on inflow conditions.
[d]Calculated from Lapp et al. (1976)
[e]Calculated from Lapp et al. (1976)
[f]Ranged from 61 to 116°C.
[g]Ranged from 18 to 59%.

2.5 FLUIDIZED AND SPOUTED BED DRYING

2.5.1 INTRODUCTION

When a fluid flows upward through a packed or fixed bed of particles, it flows through the void spaces between the particles if the flow rate is low. As the flow rate increases, particles move apart and some start to move about in small regions. The volume of the bed has increased and the bed is called an expanded bed. As the flow rate is increased further, a situation is reached when all the particles are just suspended in the flowing fluid. At this incipient or minimum fluidized condition the drag force between a particle and the fluid counterbalances the particle weight. At the same time the vertical component of the compressive interparticle force vanishes. The pressure drop at any part of the bed becomes approximately equal to the weigth of the fluid and particles in that part.

In most gas-solid systems a further increase in gas velocity results in large instabilities with bubbling and channeling of the gas. At still higher flow rates the bed behaves as a boiling liquid and the bed is said to be gas fluidized or heterogeneously fluidized. A unique charateristic of the bed is that it has liquidlike properties; for example, when two gas fluidized beds are connected, their levels will equalize.

Fluidized beds are widely used in industry to carry out gas-solid reactions because the rapid mixing of solids results in near isothermal conditions throughout the reactor, high rates of heat and mass transfer between the gases and particles, and ease of continuous, automatic operation. One of the major disadvantages is the relatively high pressure drop caused by the fluid's support of the solids. Nevertheless, the use of fluidized beds is so widespread in industry that Zenz (1984) was able to

list no fewer than 216 different applications in the petrochemical, pharmaceutical, metalurgical, mining, and energy production industries. At present some 200 fluidized bed catalytic cracking plants are in operation in the world and 35 major U.S. companies have designed and built large fluidized bed coal combustion equipment. Zenz (1984) also listed some 36 installations used for drying and sizing of dolomite, limestone, cement, blast furnace slag, oyster shell, ilmenite, chlorinated hydrate, sand, detergents, iron ore, phosphate rock concentrate, alumina, plastics, salt, and a variety of other chemicals. The capacity of the units varied from 0.25 to 500 t/h, while the contacting schemes include countercurrent contacting, crosscurrent contacting, or solid circulation.

Beds of large uniformily sized solids often fail to fluidize unless a small amount of fines are added to act as a lubricant. Instead, if the flow of gas or liquid at the bottom of a bed of coarse particles ($d > 1$ mm) is high enough, the jet of fluid will carry a stream of particles through the central core of the bed. Usually the particles will be carried above the bed surface and fall back onto the annular surface area outside the core. The flow of particles in the core resembles a spout so that the bed is called a spouted bed. After the particles return to the annular surface of the bed, they slowly move downward and eventually are reentrained into the spout. The industrial use of spouted beds overlaps with that of fluidized beds, especially when the particle size prohibits the formation of good fluidization. For example, gas-spouted beds have been used to preheat coal feed to coke ovens, to granulate and cool fertilizers, to granulate pigments and dyes, to coat pharmaceutical tablets, to coat urea granules with sulphur to produce slow release fertilizer, to thermochemically coat pyrolytic carbon and/or silicon carbide onto nuclear fuel kernels of uranium oxide, to

coat prosthetic devices, and to produce cement. These and other applications, some of which are still in the experimental stage, have been described by Mathur and Epstein (1974) and Epstein and Grace (1984).

It is however interesting to note that the spouted bed process was originally developed at the National Research Council of Canada for the drying of wheat (Mathur and Gishler, 1955). Until that time spouted beds had been observed as an interesting but undesired phenomenon in fluidized beds.

A complete treatment of the theory of fluidization has been presented by Othmer (1956), Leva (1959), Zenz and Othmer (1960), Davidson and Harrison (1963), Kunii and Levenspiel (1968), and Grace and Matsen (1980). Fluidized bed drying has been dealt with by Vanecek et al. (1966). Spouted bed theory and applications were presented by Mathur and Epstein (1974). Design of fluidized and spouted bed processes and equipment have been presented in various handbooks, including the Handbook of Powder Science and Technology by Fayed and Otten (1984).

2.5.2 SPOUTED BEDS

a) Original work

As mentioned above, the first application of gas-spouted beds was in the area of wheat drying. It was the direct result of observations that wheat kernels, which are large and uniform in size, tended to rise up as slugs instead of becoming fluidized. The interest in developing a fluidized wheat dryer was based on the premise that vigorous agitation of the kernels would result in higher drying rates as well as more uniform drying of all the kernels. Failure of being able to fluidize wheat kernels led to an investigation of using a spouted bed to dry wheat. It was assumed that the continuous agitation and cyclic motion of the kernels within the bed would

allow the use of much higher drying tempertures than could be used in conventional heated air dryers without overheating the kernels. That is, the kernels would only be exposed to the hot air stream for a short time before being transported out of the core (Mathur and Gishler, 1955).

After conducting experiments on spouting of beds of wheat in cylindrical columns ranging from 150 to 600 mm in diameter and evaluating the motion of the kernels, including velocity profiles and pressure drops, a 300 mm diameter pilot wheat dryer was constructed. The complete unit consisted of a spouted bed dryer, a cooler, an air heater and airflow controls. The dryer was made of a metal column and a conical base through which the heated air entered the bed. The air inlet was a 6.4 mm diameter opening at the base of the 85 degree (included angle) cone. The cooler was 230 mm in diameter and was connected to the dryer with a 38 mm diameter pipe through which the dry wheat passed, thus maintaining the desired level in the dryer. Wet wheat from a hopper was fed into the dryer through a pipe placed against the inside column wall. The opening of the pipe was about 300 mm below the bed surface so that the wheat had to make at least one pass through the spouted bed before being discharged to the cooler. Airflow to the dryer was about 3.5 m^3 of air/min and to the cooler 1.5 m^3/min. Experiments were conducted with bed depths ranging from 300 to 1200 mm, feed rates of 90 to 270 kg/h, moisture contents of 20 to 36% (dry basis), and air temperatures of 100 to 180 ^{o}C.

One of the observations made was that 300 and 600 mm deep beds resulted in kernel damage because the wheat spent too much time in contact with the drying air, which was kept at 150 ^{o}C for the variable depth runs. It was concluded that shallow beds required lower drying temperatures. In the

temperature series of runs with a 1200 mm deep bed, in which the feed rate was increased proportionately to maintain a constant decrease in moisture content of the feed, the rate of water removal increased with air temperature. Thus, the water removal rate increased from 4.2 to 8.2 kg/h in the dryer and 1 to 3.9 kg/h in the cooler as the drying air temperature was varied from 100 to 180 °C. At 180 °C a total of 5.6 percentage points of moisture was removed at a feed rate of 270 kg/h. It was also reported that the thermal efficiency of the dryer and cooler was about 65% using 21 °C as the base temperature but no data were given to show how this was calculated.

Although the experiments were deemed to be successful and the patent rights were assigned to the Canadian Patent Development Corporation, N.R.C., Ottawa, the spouted bed dryer had a major problem as far as pressure drop was concerned. The total pressure drop in mm of water was nearly half the height of the spouted bed of wheat. In order to supply sufficient air at those pressures, high pressure, large volume fans or compressors are needed. These air movement units are expensive to purchase and operate.

b) Further work

Subsequent work at N.R.C. dealt with drying of barley and peas (Saunby (1958) and Peterson (1959)). As a result two commercial spouted pea dryers were installed in Canada which were still operating ten years later (Mathur and Epstein, 1974). Peterson (1962) used one of the commercial dryers to obtain drying data on peas, lentils and flax. These results were compared with the barley data and the wheat data of Mathur and Gishler (1955).

The commercial unit was essentially of the same design as the pilot plant developed by Mathur and Gishler (1955). That is, a 610 mm diameter dryer and a 910 mm diameter cooler were placed side by side. The dryer

contained a 2100 mm deep spouted bed and the cooler a moving packed bed. In addition to determining equations to predict the airflow required for spouting and the kernel temperatures, the efficiency of the complete unit was found to very from 4190 kJ/kg of water for peas to 8840 kJ/kg of water for seed peas. Similarly, the drying capacity was found to vary from 24 kg of water evaporated/(m^3 of grain.h) for seed peas to 112 kg/m^3.h for yellow peas. These capacities were compared by the authors to a value of 8 kg/m^3.h for farm batch dryers and 32 to 100 kg/m^3.h for rotary dryers. The cost of drying peas at the rate of 500 kg/h through 8.8% was estimated to be 0.44 cents/kg with 60% of the cost being due to operating and 15% to energy use. It was also mentioned that 65% of the capital cost was for the blower and burner and that a cascading type dryer of similar capacity would cost up to three times as much.

Becker and Sallans (1961) published the results of spouted bed drying of wheat. The laboratory-scale dryer was 230 mm in diameter and was operated at air temperatures of 97 to 170 °C; however, the grain temperature did not exceed 45 to 75 °C. In drying wheat with an initial moisture content of 25% (d.b.) to 15-19%, the dryer capacity was found to be 28 to 43 kg/h.

Similarly, Kugo et al. (1965) performed batch and continuous flow experiments with wheat in a 150 mm diameter spouted bed. Various moisture contents mass flow rates, air temperatures and airflow rates were examined.

c) Recent work

Despite the apparent success in drying peas, wheat, lentils and flax with a spouted bed system, the method was not developed beyond the initial applications. Aside from the above references there appears to be little information in the literature of the 60's dealing with the application of

spouted beds to agricultural products, although a large amount of research was published on the fundamental behaviour and use of spouted beds in other industries.

The agricultural interest in spouted beds resurfaced in the 70's in terms of drying rice. Thus, in Japan, Yamaguchi and Wakabayashi (1972) investigated the pressure drop and airflow in spouted beds of unhulled rice. In the United States, Chhinnan et al. (1977) attempted to make use of the high drying temperatures allowed in spouted beds to increase the drying rate of rice. They discovered that the milling quality was not affected when rice was dried at 60 °C.

Work on drying of paddy rice in the Netherlands (van Brakel, 1980) led to the use of the draft tube spouted bed, which had been used by Buchanan and Smith (Mathur and Epstein, 1974). In a spouted bed with a draft tube, the bed-annulus interface is replaced by the wall of the draft tube, except for the lowest part where the particles enter the spout. The result is that less air is needed to keep the solids circulating in the bed and the bed depth limitation caused by the rapid decrease in momentum of the conventional spout is removed. Therefore, the draft tube spouted bed will allow much deeper beds. Khoe and van Brakel (1980) used a 300 mm diameter vessel with a conical bottom having a 45 degree inclined wall and a 25 mm diameter air inlet. A 53 mm diameter, 1.5 m long draft tube was installed in a way that allowed variation of the opening between the bottom of the tube and the conical base. Batch experiments were carried out with 45 kg of Italian round grain paddy to determine the hydrodynamic and drying characteristics of the bed. The drying air had an inlet temperature of 160 °C but the rice temperature did not exceed about 65 °C. The results led to the conclusion that there was a linear relationship between the decrease in

moisture content and time when the rice was dried from 30 to 15% (d.b.). This means that the drying rate was constant instead of being a falling rate as observed in experiments without the draft tube (van Brakel, 1980). In a subsequent publication Khoe and van Brakel (1983) reported additional observations. They concluded that 70% of the total heat transfer between the air and the particles occurred in the recirculation zone and 30% in the draft tube as the particle passed through them in about 0.2s. A moisture gradient was established inside the particle while in contact with the air stream. As the particle travelled downward through the annulus in about 360 s, moisture diffused to the surface and evaporated, keeping the air in the annulus highly saturated. Hence the drying rate was completely determined by the heat transfer in the recirculation zone and the tube so that the drying rate became constant. The efficiency of the dryer was found to vary from 34 to 62% depending on operating conditions.

d) Two-dimensional spouted beds

In an attempt to reduce the pressure drop in cylindrical spouted beds, Kalwar et al. (1986) investigated the use of a two-dimensional spouted grain dryer. The bed was constructed of plexiglass and was 0.75 m long, up to 0.47 m wide, and 2.00 m high. The air entry was a slot along the width of the slanted base. Static experiments with beds of corn, soybeans, and wheat with moisture contents of 14.8, 14.8 and 13.8%, respectively, showed that the static vertical pressure increased as the bed length to slot width aspect ratio increased at the same base angle. The static vertical pressure was also shown to depend on the base angle, bulk density and sphericity of the grain, and the bed height. After additional experimental work with asymmetric two-dimensional spouted beds of wheat, corn, oats, and barley,

Anderson et al. (1986) presented pressure drop-velocity data. It was concluded that the pressure drop-velocity plots showed the same hysteresis and shape as conventional spouted beds. A preliminary drying experiment using ambient air and beds of corn and wheat showed that the grain dried 50% faster than in a stationary bed. However, no work was done on heated air drying and no energy data were presented.

2.5.3. FLUIDIZED BEDS

As mentioned above, grain is difficult to fluidize because the kernels are too large and too uniform. Therefore, most researchers have considered spouted beds instead. There are however some references in the literature to fluidized bed crop drying. For example, Ulku and Uckan (1986) developed a theoretical model to describe the drying of shelled corn in a fluidized bed and tested the model experimentally using various air velocities and temperatures of 20 to 65°C. The laboratory-scale fluidized bed consisted of a plexiglass cylinder, 88 mm in diameter and 400 mm long. The results indicated that the drying rate was indeed higher than calculated for a conventional heated air dryer. However, more importantly, the pressure drop at the minimum fluidization velocity of 1.1 m/s was about 400 Pa. Such a high pressure drop severely restricts the use of fluidized beds in drying large quantities of grain.

2.5.4 SUMMARY

1. Fluidized beds are generally not suitable for drying grain because the kernels are too large and uniform.

2. Spouted beds have been used to dry wheat, barley, peas, lentils, flax, and rice. Two commercial spouted pea dryers were in operation in the

60's and the early 70's (See Table 2.5.1).

3. Advantages of spouted beds over conventional high temperature drying include higher drying rates and uniform moisture contents. The reasons being that

a) higher air temperatures can be used because the kernels are exposed to the spout environment for less than one second of the turnover cycle;

b) internal moisture and temperature gradients become uniform during the downward travel in the annulus;

c) all kernels are exposed to the same environment and are completely mixed;

4. Main disadvantages of spouted bed dryers are the high pressure drops (about half the height of the bed in mm of water) and airflow rates but these may be reduced by using a draft tube or other modifications.

5. Based on limited information, it appears that the specific energy consumption is of the same magnitude as in high temperature drying.

6. Further research is required to evaluate the drying charateristics of the two-dimensional spouted bed and to improve the performance of the draft tube spouted bed.

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Table 2.5.1 PARTIAL SUMMARY OF SPOUTED BED DRYING

Material dried	Bed geometry (mm) dia.	height	Moisture content (%, d.b.) initial	final	Feed rate (kg/h)	Airflow (kg/h)	Temperature (°C) Air	Solids	Reference
Industrial scale									
peas	610	2140	23-68	21-47	1000-1700	2600-3100	124-284	45-78	Peterson (1962)
lentels	610	2140	25	17	1160	1470	297	69	
flax	610	2140	35	14	890	1600	448	67	
Laboratory scale									
wheat	300	300-1200	20-36	17-29	110-270	242-278	100-180	38-54	Mathur and Gishler (1955)
wheat	230	910	25	15-19	28-43	143-156	97-170	45-75	Becker and Sallans (1961)
wheat	150	90-210	20-44	4-12	batch	35-53	60-180	-	Kugo et al. (1965)
wheat	150	610	21-30	14-18	1.8-3.6	35	70-145	-	
rice	300	1500	30	15	batch	-	160	65	Khoe and van Brakel (1980)

2.6 USE OF PRESERVATIVES IN LOW-TEMPERATURE DRYING

2.6.1 INTRODUCTION

Chemicals such as sulfur dioxide, propionic acid, methylene bis-propionate, formalin and ammonia can be used to inhibit the existence and growth of microflora commonly found on corn. Although most of the work was done on the preservation of high-moisture grain to be used as animal feed, inhibition of microflora would also allow an extension of the low-temperature drying period. This will allow more efficient use of favourable weather conditions while deterioration will be reduced during less favourable conditions.

There are three methods used to apply the chemicals to grain: the trickle method, the reverse trickle method and the auger method. Each of the methods will be described and the work done with various chemicals will be reviewed.

2.6.2 METHODS OF APPLICATION

The "trickle" procedure was developed for the use of anhydrous ammonia on corn by Nofsinger et al. (1977,1979). The gas is injected into the drying air stream and is carried through the grain where it acts upon the indigenous microflora. This procedure requires little equipment modification to a low-temperature drying system. Some advantages of this system include the excellent control of the gas as well as the possibility of intermittent application of gas throughout the drying and storing processes. The major drawback of this system is that the highest concentration of gas occurs in the bottom layers of the bin. Since this corn is dried first, it does not need to be treated. Another disadvantage is that a considerable amount of gas is expelled in an effort to attain the proper levels of gas in

the top layers.

With a few modifications, the trickle method can be inverted to form the reverse trickle method. It is more efficient because the gas is released in the head or top space of the bin and is drawn through the grain to the bottom layers. This means that the fan must be altered to allow reverse airflow while the gas is being released and then be reset to allow normal drying of the grain. The system offers the advantage of exposing the grain that needs the most preservatives to the highest concentrations of gas for the longest time. Once the concentration of gas breaks through to the bottom layer the system can be shut down with little waste of gas. With this method retreatment to keep the microbal activity low is also possible so that the user is able to apply preservatives in response to the prevailing weather conditions.

In the auger method chemicals are sprayed on the corn as it is loaded into the bin. Each different layer may be given different concentrations but once the bin is loaded no further treatments are possible unless it is used in conjunction with a trickle process. This means that a estimate of the quantity of preservatives added to the corn must be made without knowing the weather conditions that will be present during the drying period. Since a large single dose is used, this method takes the largest amount of preservatives.

The grain may also be soaked in an aqueous preservative solution. This process will raise the moisture content and is therefore not efficient if used in conjunction with a drying process. It is more applicable to high-moisture storage of grains without subsequent drying.

2.6.3 AMMONIA

An advantage of using ammonia for the preservation of corn is that it has a strong affinity for water. This means that the largest amount of NH_3 will reside where the concentration of water and thus microbial activity is the highest. It also means that if the grain is being dried at low temperatures, there is no need to deodorize the corn before feeding it. In all the grain preservation studies NH_3 worked as an excellent antifungial agent and as a satisfactory antibacterial agent by lowering the pH.

Nofsinger et al. (1977) studied ammonia-supplemented ambient temperature drying of high-moisture corn. They were able to control microflora on the corn for six months without corn spoilage while allowing drying to continue. Ammonia concentrations below 0.1% were not corrosive to the unprotected galvanized bin surfaces but concentrations of 1.5 to 2% were corrosive. They believed that smaller doses every 3 to 5 days would be more efficient than one large single dosage. Their use of the trickle method was reported as simple and required a modest capital investment while complementing existing low-temperature drying systems.

Peplinski et al. (1978) reported the result of an experiment to store high-moisture corn (23%) for fourteen months at ambient temperatures ranging from 16 to 39°C. Initially, the corn was treated with 1% aqua ammonia using the auger method which raised the moisture content to 28%. Further periodic applications of small amounts of anhydrous ammonia were made to keep microflora and spoilage under control. The corn color was observed to change to deep brown after only 4 days. Also, the free flowing characteristics of the corn reduced as time progressed. It was suggested that in the future, a stirring device would eliminate this problem as well as reduce any ammonia or moisture gradients. Free flowing characteristics did return after the

grain was unloaded. The total aqua and anhydrous ammonia added to 4036 kg of corn was 3% by weight. A rapid temperature rise was noted in the first 10 days of storage and it was suggested to be chemical in origin. The grain was subsequently cooled by aeration and returned to a temperature range of 20 to 47°C while ambient air varied from 16 to 39°C. It was also observed that NH_3 acted as a lasting fungistal while temporarily controlling bacterial growth. Upon removal the grain had large temperature, ammonia and ammonia odor gradients with the top containing the most water and NH_3. The NH_3 process increased the nonprotein nitrogen content by 0.68% which might increase the nutritional value for ruminant feed. For example, Huber (1975) and Huber et al. (1973) reported that the treatment of high-moisture grain with NH_3 had the additional advantage of giving silage a superior feeding value by increasing the nonprotein nitrogen content of the grain.

Brekke et al. (1979a) researched five different ways of deodorizing ammoniated corn: a) drying the corn with heated non-recirculating air, b) drying the corn with heated recirculating air, c) roasting the corn in a manner used by Costa et al. (1976) and Hatfield and Wilson (1972) to improve its nutritional value, d) steaming and drying the corn, and e) chemical treatment such as neutralization of NH_3 with an acid, such as acetic acid. Upon comparison of the different methods it was concluded that drying with non-recirculating air was the most efficient and least costly. Thus a common batch-in-bin dryer can be used to obtain a 13 to 15% moisture content and a residual water-extractable ammonia ($WE\text{-}NH_3$) level of 0.25% or less. This level of $WE\text{-}NH_3$ has been found to be acceptable for feeding purposes. For example, Brekke et al. (1979b) showed that in ammoniated corn used to feed laying hens, the maximum $WE\text{-}NH_3$ was about 0.5% on a dry whole corn basis.

Similarly, Jensen et al. (1977) found that swine decreased their consumption of ground mixed ration feed. as the WE-NH_3 increased from 0.13 to 1.2% d.b.(whole corn basis).

VanCauwenberge et al. (1982) compared the trickle ammonia and trickle sulfur dioxide processes of drying high-moisture corn. They found that only small to negligible increases in nitrogen and sulfur content were detected in the corn with the trickle method. NH_3 treated corn had a germinability below 80% and exhibited a light burnt orange color. SO_2 changed the colour to a lighter yellow and caused the thiamine content to drop from 0.45 to 0.26 mg/100 g but did not reduce the germinability. It was also observed that after a short period the NH_3 gas followed channels through the grain and as a result did not readily disperse throughout the corn mass. This problem was not observed when the corn was periodically stirred. In feeding trials steers gained weight more rapidly but less efficiently on control corn than on NH_3 treated corn. They concluded that the NH_3 system was readily available, low costing and easily handled, more so than a SO_2 system. Although the SO_2 process was more effective in reducing microbial activity, it was also more corrosive to metal. All trickle methods investigated using SO_2 or NH_3 were found to be cost effective and efficient for drying of high-moisture corn.

Since ammonia in aqua or gaseous form is toxic and may cause health problems, Ghate and Bilanski (1981) suggested using urea as an alternative and less hazardous source of ammonia for preservation of high-moisture corn used as animal feed. Presumably, the same approach could be used with low-temperature drying of wet corn.

2.6.4 SULFUR DIOXIDE

Sulfur dioxide treatment is an excellent means of preserving and is used for such products as fish, beverages, fruits, vegetables and meats (Schroeter, 1966). SO_2 is effective in the control of microorganism since it modifies the pH and blocks emzymatic activity. Unlike ammonia, SO_2 destroys bacterial life for greater periods of time while, like ammonia, it has an affinity for water and is therefore concentrated where the preservative is needed. Corrosion of unprotected metal is a problem with SO_2 use. In addition, special care must be taken in the use and handling of sulfur dioxide.

Eckhoff et al. (1980) reported that corn had no decrease in quality from the use of the trickle processes as determined by official grading, fatty acid analysis, thiamine analysis, and dry milling results. Samples of SO_2 corn were submitted to an official U.S. licensed grain inspector and were categorized as No. 1 yellow corn while the control and salvage corn samples were reported to be significantly damaged by molds. There was no difference in fatty acid content of all the samples. Thiamine was reduced by 35% in the SO_2 and salvage corn. No significant increase in sulfur content was reported. Based on microscopic examination of colonies, it was decided that SO_2 was more effective for mold control than for bacteria control. In fact, spore-forming bacteria were resistant to the levels of SO_2 used in the study.

Eckhoff et al. (1984) also tested sulfur dioxide as a mycocidal adjunct for low-temperature grain drying. They studied the process using the trickle, reverse trickle and auger methods of applying SO_2. In both trickle methods 6.1 kg SO_2 was applied over a 2 h period for a mean concentration of 0.12% (wt SO_2/wt wet corn). After applying the chemical, the fans were

turned off for 20 h to allow eradication of microflora present and the absorption of SO_2 onto the corn. After 28 and 128 days the trickle bins were retreated with 0.05% SO_2 injected within one hour (287 ml/s) after which the fans were left off for 20 h. Both trickle methods showed microbial growth at the lower limits of detection for most tests performed. The trickle bin had a moldy spot 3 m in diameter and 0.2 m deep at the top center of the grain where the moisture content was 29%. For the reverse trickle method no growth was noted above or below the surface. For the auger method the bottom 1/3 layer was untreated, the middle 1/3 was treated with 0.1 % SO_2 (wt SO_2/wet wt corn) and the top 1/3 received 0.2% SO_2 giving the bin an average dosage of 0.23% by weight or 7.9 kg of SO_2. After only 128 days the corn had visibly molded. They decided to retreat the corn by releasing gas at the top of the bin and allowing SO_2 to filter through by gravity (SO_2 is 2.264 times heaver than air). This method was completely unsuccessful because most of the gas spilled over the top of the bin instead of dispersing throughout the grain. The auger method used the most SO_2 and did not stop microbial growth. The reverse trickle method was the only procedure to perform successfully based upon mold count, mycotoxin analysis, and grading. The breakage susceptibility increased from 6.9 to 10.1% with the SO_2 treatment while that of high-temperature dried corn increased from 6.9 to 31.5%. Tests were performed to evaluate the corrosion of the unprotected and linseed oil coated galvanized steel. Corrosion was observed in both instances but was inhibited by the linseed oil. It was suggested that more research was needed to determine the extent of protection required for a system.

2.6.5 OTHER CHEMICALS

Anoher chemical that effectively inhibits mold activity is sorbic acid, when applied as a solution. The salts of sorbic acid, especially potassium sorbate, are of interest in preserving high-moisture grain because of their high solubility in water. For example, Danziger et al. (1973) showed that 0.05 to 0.20% potassium sorbate increased the safe storage time of grain corn. More recently, Yasin and Hanna (1984) treated high-moisture corn (19, 24 and 28%, w.b.) with different levels of potassium sorbate or potassium sorbate plus propylene glycol. In addition they considered the effect of aeration and no aeration on the storage time. Both treatments, potassium sorbate or potasium sorbate plus propylene glycol, prevented the growth of molds on corn until the conclusion of the experiment, 233 days later. This chemical treatment caused a slight darkening and an increased breakage susceptibility of the corn. It was suggested that this method of preservation could be used in conjunction with a low-temperature dryer, but no drying experiments were performed.

Hall et al. (1974) used a mixture of propionic and acetic acid to preserve high-moisture corn. They concluded that subsequent drying at temperatures ranging from 40 to 100 ^{o}C left an acid concentration of 0.4% on a dry matter basis. In feeding trials, cattle showed a significantly lower average daily gain at acid levels of 0.6%; while the presence of acid did not influence feed consumption or palatability in feeding swine.

2.6.6 ECONOMICS

Hsieh et al. (1979) stated that the specific energy consumption of their low-temperature ammonia drying system was 3696 kJ/kg water removed. This was said to be 50% less than the 7500 kJ/kg observed by Kalchik et al.

(1979) for their high-temperature drying system. Eckhoff et al. (1980) approximated that an energy saving of between 2.8 x 10^8 to 5.6 x 10^8 J/t can be realized by using a SO_2 trickle method instead of a high temperature drying system which required 7.5 x 10^8 J/t. Eckhoff et al. (1984) calculated that cost savings of $7.38/t was expected over an automatic batch dryer and only $3.00/t over a natural air combination drying system. The consensus of the researchers is that the use of preservatives to store and aid low-temperature drying is economically advantageous; however, the fact that SO_2 is corrosive to metals and will reduce the useful life of any system may add to the cost.

2.6.7 CONCLUSIONS

1. Both ammonia and sulfur dioxide have been shown to be effective preservants of high-moisture corn and can be used in existing low-temperature drying systems with little additional equipment.

2. Little low-temperature drying research has been done on the use of preservatives other than SO_2 and NH_3.

3. The reverse trickle method was most efficient in the control of microbial activity.

4. The auger method of application showed unsatisfactory results in all research situations.

5. Ammonia has been shown to be not corrosive to metals in small concentrations but sulfur dioxide is extremely corrosive to the drying and storage bins.

6. More research is required to determine the amount of corrosion protection needed for a satisfactory system life.

7. Small periodic applications of preservatives is better than one

large dose for control of grain microbial activity.

8. Ammonia treatment increased the corn breakability but less than the SO_2 or high-temperature drying treatments.

9. Ammonia caused slight darkening of corn, while sulfur dioxide caused slight brightening.

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3.0 HEAT RECOVERY SYSTEMS

3.1 INTRODUCTION

Continuous-flow, high-temperature dryers exhaust large quantities of saturated and partially saturated exhaust from their drying and cooling sections. One obvious way of improving the energy efficiency of those dryers is to recover energy from the exhaust streams. The most efficient method of recovery is to recycle the exhaust directly. This is possible with the cooling air and partially saturated drying air. It is of course not beneficial to recycle the saturated and near saturated drying air without first removing a significant amount of the water vapour. Dehumidifying the exhaust may be done with a heat exchanger or a heat pump after which the air could be recycled in a closed-loop system. Instead of dehumdifying the air, the same equipment could also be used to extract the latent and sensible heat and transfer it to a fresh ambient airstream in an open loop system.

In general, recycling of cooling air and partially saturated exhaust has been widely applied to high-temperature, continuous-flow dryers, while most of the heat pump applications have been restricted to low-temperature drying. Some work has been done on the use of heat exchangers in recovering latent heat from the saturated exhaust of high-temperature dryers.

The following review of the heat recovery systems will consider recycling, use of heat exchangers and heat pumps separatedly; however, there are cases in which two or even all three situations occur simultaneously.

3.2 RECYCLING OF COOLING AIR AND EXHAUST

Recycling of the cooling air and the unsaturated drying air may be accomplished by redesigning the air plenums or by enclosing the drying system and rerouting the airflows. The cost of the changes varies depending upon

the type of dryer and whether or not the modifications are retrofitted or included in the design.

3.2.1 THEORETICAL INVESTIGATIONS

One of the earlier references to recycling is due to Bakker-Arkema et al. (1974). They compared a conventional counterflow dryer with a modified recirculating counterflow dryer and found that the specific energy use (kJ/kg of water removed) of the latter was up to 16% lower at the same operating conditions.

Meiering et al. (1977) used batch and continuous flow simulation models to predict the performance and net energy consumption of popular farm dryers with and without air recycling. One of the batch dryers modelled was of a German design which was unique in that it had a column width of only 0.1 m as compared with the standard 0.45 m. In operating the dryer a batch of grain makes two passes through the drying colum and is cooled between passes and at the end of the second pass. As shown in Table 3.2.1, recycling the cooling air resulted in an energy consumption of 3249 kJ/kg of water removed or a savings of 24% as compared with operating the dryer without recycling. Although the dryer was designed to allow recycling of part of the unsaturated air from the drying section as well, insufficient information about the recycling procedure prevented modelling of the dryer under those conditions. It is expected however that the energy savings would be increased further.

In the same publication, the authors compared the performance of a popular dual column, continuous, crossflow dryer in which corn is dried in a single pass. In this instance recycling of the cooling air resulted in a calculated energy savings of 17%. It was also pointed out that a ducting

system to achieve air recycling can be installed with little effort.

Meiering et al. (1977) also modelled the performance of a single-stage, concurrent-flow farm, dryer and a three-stage, concurent-flow, commercial dryer (the Westlaken dryer). Energy savings of about 10% and 9% were predicted for the farm and commercial dryer, respectively, when the cooling air was recycled.

Brook et al. (1977) used a dynamic programming optimization scheme to determine the optimum operating parameters and dimensions of a multistage, concurrent-flow dryer. They included the situation in which the exhaust air from one drying stage became the input air to the heater of the next drying stage. It was determined that the extra humidity in the inlet air to each drying stage had little effect on the amount of drying; however, recycling decreased the energy consumption by 11 and 16% at corn flow rates of 2.5 and 4 $t/h.m^2$ of dryer area, respectively (see Table 3.2.1).

A review paper by Peart et al. (1977) dealt with the energy requirements of various grain drying systems. They predicted that a crossflow dryer in which all the cooling air and the exhaust from the bottom 50% of the drying column were recycled, would use 15% less energy than without recycling. For example, when corn was dried from an intial moisture of 30% to a final one of 14%, a crossflow dryer with reversed cooling was simulated to use 1288 MJ/t and one with recycling 1090 MJ/t.

3.2.2 LABORATORY STUDIES

Converse (1972) used a modified laboratory crossflow dryer consisting of three separate modules, two of which were used for drying and one for cooling. The exhaust from the cooling module and the middle module were mixed and heated to 143 ^{o}C. The heated air was then divided into two streams

with one going to the first module and the other one to the second module. Lerew et al. (1972) simulated the performance of the dryer and found a 50% reduction in energy consumption as compared with operating the dryer without recycling.

Bakshi et al. (1978) also used a laboratory-scale version of a three-stage, crossflow dryer with recycling of the exhaust air from one stage to the other stages to dry rice with a moisture content of 30%. Various configurations of dryer operation were tested. One comparable set of tests showed that recycling the air from the second stage to the first stage resulted in a specific energy consumption of 4480 kJ/kg instead of 6170 kJ/kg for a no-recycling condition. A further reduction to 3570 kJ/kg was achieved by recycling the exhaust from the first two stages to the third one. It was also pointed out that the rice dried more uniformly throughout the dryer when the air was recycled to the previous stage.

3.2.3 RECYCLING IN COMMERCIAL DRYERS

The benefits of recycling part of the exhaust and all of the cooling air were sufficiently obvious and involved such modest investments that much of the original work was done on full-scale commercial dryers. Thus, Bauer et al. (1977) determined the operating characteristics and thermal efficiency of a 4500 bu recirculating, crossflow dryer. The FR 4500 Town and Country dryer which is manufactured by Ferrell-Ross, Saginaw MI, consists of six drying sections and two cooling sections. In order to reduce the moisture gradient across the column of the dryer, the airflow direction in the first, second, fifth and sixth sections is opposite to that in the third, fourth, seventh and eighth sections. The exhaust from the second through the fifth drying sections and one cooling section was recirculated

to the drying fan. In this way the recycled air accounted for 50% of the total drying air. Experimental data were collected in 1976 during normal operations over a period of 40 days in which nearly 20,000 t of wet corn were dried from 28.4 to 14.4%. It was concluded that the specific energy consumption without recirculating was about 7440 kJ/kg of water removed and with recirculating 5470 kJ/kg for an energy savings of 27%.

In 1978 the same dryer was retested and compared with the performance of the T&C-4000, which had no air recycling and was the forerunner of the FR-4500 (Bakker-Arkema et al. (1979)). The average energy consumption over the entire drying season was 5070 kJ/kg for the FR-4500 and 7210 kJ/kg for the T&C-4000, a savings of 30%.

In describing the features of the SUPERB tower dryer, Noyes (1977) pointed out that the design of this continuous, crossflow dryer included recycling of all the cooling air and 40-50% of the exhaust from the lower half of the drying column. In testing a model S6-100 he found a specific energy consumption of 4880 kJ/kg when drying about 34 t/h of wet corn with an intial moisture content of 19.9% to a final one of 13.9%. In subsequent tests of three S7-150 model dryers, the energy consumption in drying about 35,000 t of corn from 20 to 14.5% was 4400 kJ/kg at an average capacity of 47 t/h (reported in a review article by Hawk et al. (1978).

Otten and Brown (1978) made a simple modification to an ACE crossflow dryer (manufactured by Dorssers Welding Co. Ltd., Blenheim, Ontario) so that the air leaving the cooling section was deflected to the drying fan. Without the deflector the dryer used an average of 5090 kJ/kg in three performance tests in 1977 while drying 39 t/h of corn from 24 to 15%. In comparison, the average energy consumption in three tests in 1978 was 4310 kJ/kg and the

capacity was 41 t/h with corn being dried from 29 to 14.5% (Otten et al., 1980). Unfortunately, the drying temperatures were different in both years (68 °C in 1977 and 84 °C in 1978) so that the energy savings of 15% was only partly due to the recycling of the cooling air. Nevertheless, as a result of the work, the manufacturer redesigned the dryer to allow for recycling of all of the cooling air and the exhaust from the bottom 25% of the drying columns. Performance tests were run on the new design (ACE model 2165-D) as part of an emission study. Otten et al. (1983) determined that the specific energy consumption was 4480 kJ/kg when corn was dried from 30 to 17% at an air temperature of 110 °C.

Otten and Brown (1980) also evaluated the performance of two farm-scale dryers with cooling air and exhaust recycling. One dryer was the Belt-O-Matic, which is a belt type dryer. Since the grain is dried on a moving belt, the unit is basically a crossflow design with a single column of grain placed in a horizontal position. Air from the cooling section and part of the exhaust is recycled. The amount of exhaust recovered depends upon the position of a sliding roof above the drying section. Therefore, the amount of recirculated exhaust is readily adjusted as the drying conditions and initial moisture content change. Two sets of tests with different bed depths and drying temperatures were run to determine the dryer performance. At a corn depth of 230 mm and a drying temperature of 116 °C, the specific energy consumption was 4680 kJ/kg and the capacity was 1.6 t/h. At a depth of 150 mm and temperature of 126 °C, the energy use was 4080 kJ/kg and the capacity 2.0 t/h. In both cases all the cooling air and 30% of the exhaust was recycled.

The other dryer was a four-column Behlen dryer around which an enclosure was built so that all of the cooling air and part of the exhaust was recycled to the drying fan. The enclosure was a permanent lean-to

building around both sides and the fan end of the dryer. Since the drying fan inlet was inside the building, the drawn into the fan was made up of cooling air, exhaust and ambient air. Saturated exhaust from the top 75% of the drying section was allowed to escape from the dryer through a 300 mm gap at the roof. Specific energy consumption with this design was 4010 kJ/kg while drying 2.6 t/h of 27% corn to 14.6%. Based on humidity data it was estimated that the maximum savings would be 730 kJ/kg or 18%.

According to Hawk et al. (1978) recycling can also be done in concurrent-flow and rack dryers but no energy data were provided for these dryers.

3.2.4 SUMMARY

1. Theoretical, laboratory and commercial studies have demonstrated that recycling of the cooling air and unsaturated drying air results in energy savings of 10 to 30% (see Table 3.2.1).

2. Changing existing dryers to a recycling mode may be as simple as reversing the airflow in the cooling section and adding a divider to the exhaust plenum of the drying section of commercial crossflow dryers.

3. In other cases it may be necessary to enclose the exhaust area with a plenum and/or a building.

4. Almost all continuous flow dryers have been redesigned to allow recycling as a standard feature.

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TABLE 3.2.1. SUMMARY OF AIR RECYCLING DATA

DRYER TYPE	TEMPERATURE (°C) DRYING	COOLING	AIRFLOW ($m^3/h.m^2$)	WET GRAIN FLOW (t/h)	MOISTURE (% w.b.) INITIAL	FINAL	RECYCLED (%) COOLING	EXHAUST	ENERGY (kJ/kg) NO RECYCL.	RECYCL.	SAVINGS (%)	REFERENCE
BATCH	80	10	1500	3.5	27.5	20.8	100	0	4282	3249	24	MEIERING et al (1977)
CROSSFLOW	80	10	2000	3.5	27.5	14.8	100	0	5063	4216	17	
CONC. 1-STAGE	150	10	2000	0.4	27.5	16.8	100	0	3844	3466	10	
CONC. 3-STAGE	150	10	4000	2.0	27.5	14.0	100	0	3792	3453	9	
CONC. 3-STAGE	230		2880	2.5	25	20.7	100	100	3782	3373	11	Brook et al. (1977)
	212		3600	4.0	25	22.3	100	100	3883	3277	16	
LABORATORY DRYER												
CROSSFLOW (batch)	50		1440		24	20		100	6170	4480	27	Bakeshi et al. (1978)
COMMERCIAL CROSSFLOW DRYERS												
FR 4500	80-110	-4 to 18	92.5(a)	25 31	28.4	14.4	50	50	7440	5470	27	Bauer et al. (1977)
FR 4500	107	7.3		46	24.9	15.4	50	50		5070		Baldor-Arkema et al. (1979)
T&C 400	104	9.7		37	25.1	16.1	0	0	7210		30	
S6-100	120	0	42.5(a)	34	19.9	13.9	100	40-50		4880		Noyes (1979)
S7-150	110	2	54.3(a)	47	20	14.5	100	40-50		4400		Hauk et al. (1978)
ACE	68	12-18		39	24.5	14.8	0	0	5090		15	Otten et al. (1980)
	84	8-12		41	29	14.5	100	0		4310		
ACE-MODEL 2165-D	110	5-12	2770	25	29	17	100	25		4480		Otten et al. (1983)
BELT-O-MATIC	116	3		1.6	32.5	14.5	100	30	4680			Otten & Brown (1980)
	126	2	3460	2.0	32.5	16.0	100	30	4080			
BEHLEN	93	10	1330	2.6	27	14.6	150	25	3280(b)	4010	18	

a) m^3/h at STP
b) estimated from humidity data

3.3 HEAT EXCHANGERS

3.3.1 INTRODUCTION

After recycling the cooling air and part of the unsaturated exhaust, further recovery of heat energy from a grain dryer involves the saturated exhaust. In many dryers the exhaust has a temperature of 30-40 °C and contains the latent heat used to evaporate the grain moisture. Recovery of the latent heat requires the use of a heat exchanger in which the inlet drying air is preheated by condensing the vapour; in addition, the ambient temperature during the grain corn drying season often is in the 0-15 °C range so that some sensible heat recovery is also feasible.

Because heat recovery in a grain dryer usually involves an air-to-air process and because dryer fans are usually large volume, low pressure air moving devices whose performance is readily affected by increased pressure drops in the system, the two types of heat exchangers most suitable are the shell-and-tube and the crossflow flat-plate designs. These have been used by a number of investigators in various countries; however, because the performance of a heat exchange system is closely tied to the prevailing harvest and weather conditions, only those related to Canadian conditions are presented. In addition, work done on specialized systems such as heat pipes has also been included.

3.3.2 SHELL-AND-TUBE HEAT EXCHANGER

In a shell-and-tube heat exchanger one fluid flows inside a bundle of tubes while the other fluid is forced through the shell and over the outside of the tubes. Since higher heat transfer coefficients are obtained when the shell-side fluid flows across the tubes than parallel to the tubes, baffles are placed inside the shell. A shell-and-tube exchanger can be constructed

to have the tube-side fluid pass through the exchanger more than once. Thus, in a two pass design the inlet header is split so that the fluid flowing into the tubes passes through one half of the tubes in one direction, is turned around and returns through the other half of the tubes. More complex designs with multiple shell and multiple tube passes are also used in some industries.

Winfield and Hart (1982, 1983) installed a shell-and-tube exchanger on a two-column, crossflow dryer. The initial version of the exchanger was 4.88 m wide and 3.66 m high. It contained 450 nominal 150 mm diameter, 9.1 m long, spiral galvanized pipes stacked in 25 columns, 18 pipes high. The dryer exhaust was the shell-side fluid and the incoming air the tube-side fluid. The dryer had been sized based on aiflow data provided by the manufacturer but air velocity measurements showed a peak value of only 2.3 m/s instead of the design value of 5 m/s. In comparing the dryer performance of the 1980 season, in which air recycling was used, with the 1981 data, it was concluded that the energy savings were about 14%. The exchanger was found to be self cleaning with the condensate washing the tube surface and the concrete pad below the tubes.

Before the 1982 drying season a number of design changes were made. The exchanger was divided into four horizontal sections so that the incoming cooling air was preheated by mailing one pass through the bottom 150 tubes of the exchanger. After passing through the grain the cooling air was recycled directly to the burner and accounted for 60% of the drying airflow requirements. The other 40% was ambient air that had been preheated by making three passes through the exchanger; each consisting of 100 tubes. This arrangement increased the air velocity in the exhaust tubes to 4.2 m/s,

while the velocity in the cooling air tubes was 3.5 m/s. A comparison of the seasonal data with those of 1980 and 1981 showed energy savings of 14 and 22%, respectively. However, since seasonal differences in harvest and weather conditions affect dryer performance, the authors also performed six sets of 2-hour long, back-to-back tests with and without the exchanger/recycling system in use. The corresponding energy savings varied from 16 to 41%, depending upon the prevailing ambient conditions. It was estimated that if an average savings of 33% were assumed, the savings in propane would be $11,728, which would justify an investment of 20 to 30 thousand dollars and provide a payback with interest of three years or less. However, other information provided by the authors would tend to indicate that this is an optimistic conclusion; furthermore, a significant portion of the energy savings was due to recycling of the cooling air alone. In fact the authors recommended that recycling of the cooling air should always precede the addition of a heat exchanger.

Shifflett (1986) experimented with the use of heat exchangers on a continuous crossflow farm dryer (M-C 665 EM). The dryer has two axial fans, the upper one being the drying fan and the bottom one the cooling fan although the latter could also be used for drying because a burner was installed. In the experimental work the cooling section was used to dry the grain further with air heated in the exchanger. The dryer was also fitted with an exhaust recycling system so that all of the cooling air and 25% of the exhaust could be recycled without going through the exchanger. Two different heat exchangers were used. The first one was used during the 1982 and 1983 seasons. It consisted of a pair of identical units mounted on each side of the dryer adjacent to the drying columns. The exchanger was made by placing sheets of siding metal with an H-36 profile face-to-face to form

tubular air passages in the longitudinal direction and flat air passages in the lateral direction. All but about 0.7 m^3/s of the exhaust from the dryer flowed perpendicular across the tubes through the flat passages for a distance of one metre. The 0.7 m^3/s coming from the top of the drying column was cooled to below 30 °C by the incoming corn and was therefore exhausted directly to ambient. The ambient inlet air flowed through the tubes making two passes through the exchanger for a total flow path of 9.8 m. The arrangement was essentially a crossflow exchanger with both fluids unmixed, although the two-pass feature is normally only found in shell-and-tube exchangers.

The second exchanger used in 1985 was more of a shell-and-tube design. In this case the ambient air made two passes through 32 tubes, each of which was made of lengths of 125 mm diameter residential heating ducts. The exhaust entered the shell along the entire drying section of the grain column and exited along a slot at the lower edge of the external wall of the shell. The condensate kept the staggered tubes from fouling with 'red dog' and dirt.

Experimental performance data of 1982 indicated that air recycling only resulted in a temperature rise above ambient of 16 °C, while the specific energy use was 5486 kJ/kg. Recycling plus the exchanger resulted in an average temperature rise of 28 °C and an energy consumption of 4460 kJ/kg. This represented an average savings of 19%. In 1985 the energy consumption was determined to be 4284 kJ/kg; however, seasonal differences rather than the redesigned exchanger could account for the further improvement in energy use. The author estimated that the total material cost of the 1985 exchanger was $ 3000 and the labour cost for assembly and installation was another

$ 3000. It was concluded that this investment could be recovered in 985 to 1240 hours of dryer use, which represents the single harvest operation of a 400 ha farm with an average production rate of 2534 kg of dry corn/h.

An interesting observation made by Shifflett in a set of tests in 1983 in which either one or both sides of the exchanger was used, was that the energy consumption did not change significantly. With one side operative the average value was 4033 kJ/kg and with both sides operative the average was 4136 kJ/kg. No explanation for this observation was presented.

3.3.3 CROSSFLOW EXCHANGER

McGugan (1984) presented the results of modifying a continuous crossflow dryer to recover heat from the saturated exhaust. The two-column dryer was a Fallon Model 1500 rated at 40 t/h at moisture reduction of 10 percentage points. Normally, the exhaust from the upper 8 m of the columns is discharged through a louvred section at the top of the side wall of the enclosure. The exhaust from below this point is not saturated and is recylced along with the cooling air. Before installing the heat exchanger, tests were run in 1982 to determine the various operating parameters, including the airflow rates and energy consumption. It was found that the specific energy consumption varied from 4650 to 4870 kJ/kg which compared well with the 4400 kJ/kg value claimed by the manufacturer.

The following year a crossflow, plate-type heat exchanger was installed to replace the louvred opening on one side of the dryer. The exchanger consisted of three Model MPS 120/2000 modules manufactured by Indusco Ltd., Toronto. Each module contained 250 plates (1106 x 1120 mm) for a heat exchange area of 310 m^2. Only 12 hours of experimental work was carried out in December, 1983. The only results reported were that the temperature of

the supply air increased from 0 °C to 25-30 °C and that the pressure drop of the intake side was 100 Pa and the exhaust side 125 Pa. The energy savings were estimated from the temperature rise across the exchanger and the airflow rate to be 1.3 GJ/h as compared with a total dryer energy consumption of 20 to 30 GJ/h. Therefore, the percent savings were said to be 4.3 to 6.5%. Since the cost of the installed exchanger was $56,000, the simple payback period was reported to be 9 years. However, it is clear that the experimental evaluation of the dryer was incomplete and that the results were insufficient to draw any conclusions.

MacDonald (1985) provided the results of testing a farm built heat exchanger attached to a portable Behlen KA 180 batch grain dryer. The dryer was first enclosed with a small building so that the exhaust leaving the dryer was captured. The exchanger was basically a flat plate exchanger consisting of three large plates on each side of the building. Both the intake air and the exhaust made three passes through the exhanger with both fluids flowing perpendicular to each other in any part of the exchanger. Difficulties in determining the propane consumption with sufficient accuracy resulting in inconclusive results; that is, two batches showed an average energy use of 4555 kJ/kg with the heat exchanger in operation and one batch without the exchanger showed 4360 kJ/kg. At the same time the temperature rise of the intake air was found to be 12 °C. Using temperature rise data McDonald estimated that drying of 86 batches of grain should result in a savings of 560 L of propane or $130. Since the total material cost of constructing the building and heat exchanger was $8800 plus 30 h of labour, it was concluded that the heat exchange system was not economical.

Otten (1985) used a crossflow, plate-type heat exchanger with a batch-in-bin dryer. The exchanger was designed to allow a farmer to manufacture

and assemble it without special shop equipment. The plates were made of 28 gage galvanized sheet metal measuring 1200 x 1200 mm. The plates were spaced 12 mm apart with spacers and end caps to ensure air velocities of about 5 m/s in between the plates. This velocity results in adequate values of the heat transfer coefficient and an acceptable pressure drop. The exhaust and ambient airstreams moved in a crossflow pattern through 56 airflow passages. The complete 1220 x 1220 x 1500 mm exchanger was installed in an opening cut in the side wall of the bin about 900 mm below the eave. The unit was supported by the air intake plenum so that the fresh airflow was vertically downward to the fan and burner. The exhaust passed through a set of louvres and a screen on the inside wall of the bin before going through the exchanger. The louvres and screen were necessary to prevent corn from entering the exchanger during loading of the bin and fines during drying. The system was tested by drying 11 batches of grain corn, two of which were dried without using the exchanger. It was determined that the specific energy consumption without using the exchanger was 3370 kJ/kg and with the exchanger 2580 kJ/kg. Unfortunately, the 23% savings were not enough to offset the cost of the exchanger system. It was calculated that the simple payback period is 7.6 and 11.5 years for propane and gas, respectively. Further tests of the system confirmed the above observations (Brown et al., 1987).

3.3.4 HEAT PIPE EXCHANGERS

Heat pipes are relatively novel devices and are capable of transferring large quantities of heat through a small surface area. The device consists of a sealed tube, partially filled with a working fluid. At one end of the pipe heat is absorbed from the surroundings and the fluid evaporates. The

vapour travels up the inside core of the pipe to the other end where the vapour is condensed, releasing the heat to another environment. The condensed liquid returns through a capillary wick to the heat source end. Since the overall process involves transfer of heat with phase changes, large quantities of thermal energy can be transferred from one end of the pipe to the other one. A highly efficient heat exchanger can be constructed by using a large number of heat pipes.

Lai and Foster (1977) used a custom-built heat pipe exchanger with a laboratory-scale batch dryer. The heat pipes were made of 15.9 mm diameter seamless copper tubing covered with plate-type aluminum fins. The drying system was run in an open loop configuration with and without using the heat pipe exchanger, as well as in a closed loop with a heat pump in the loop (see 3.4 Heat Pump Drying). The specific energy consumption without using heat recovery was 5470 kJ/kg and with the exchanger 5020 kJ/kg, for a savings of about 8%. This disappointing result may at least in part be attributed to the fact that the ambient air was about 25 ^{o}C and the drying temperature only 52 ^{o}C. The performance of the heat pipe exchanger would improve as the temperature difference is greater, especially when the ambient temperature is near freezing.

Based on a preliminary investigation by Bakker-Arkema et al. (1975), in which it was determined that heat pipe exchangers in concurrent-counterflow dryers could result in about 20% energy savings, Sokhansanj and Bakker-Arkema (1981) performed an experimental study as well as additional simulation work. The experimental dryer was a pilot-size concurrent-counterflow design consisting of two 357 mm diameter cylindrical columns. The drying column was 600 mm long and the cooling column 300 mm. After the

grain was dried on the concurrent section, it was conveyed with an auger to the counterflow cooler. The 3000 x 500 x 300 mm heat exchanger was made of 21 aluminum heat pipes with 4.3 fins/cm. The nominal effectiveness of the exchanger was reported by the manufacturer to be 67% at an airflow rate of 3.5 m^3/min and an overall temperature difference of 66 °C. Experiments showed that the lowest energy consumption occurred when 22% corn was dried to 19% (w.b) with complete recycling of the exhausted air from the dryer and the cooler. Under these conditions the experimental and simulated energy consumption was 3855 and 3814 kJ/kg, respectively, for an energy savings of 17.9% when compared with an energy consumption of 4695 kJ/kg without using the exchanger. Other combinations of exhaust and cooling air recycling resulted in savings of 8 to 15%. Unfortunately, a reduction in moisture content of 3 percentage points is not representative of the total drying process.

3.3.5 DIRECT CONTACT EXCHANGER

Niquet (1978) presented a description of a French dryer in which a direct contact heat exchange process was used to recover the heat from the exhaust of one dryer to preheat the air entering a second dryer. By passing the exhaust through a spray of water, the latent and sensible heat was transferred to the water. The heated water was then pumped through a water-to-air heat exchanger to heat the drying air of a second dryer. About 65% of the energy put into the first dryer was recovered and transferred to the second dryer for a savings of approximately 50% as compared with conventional dryers used in France.

Laferriere et al. (1986) simulated the performance of a similar airwash exchanger and concluded that the specific energy would decrease from 3151 to

2160 kJ/kg if 85% of the exhaust from one dryer was passed through the exchanger to preheat the air for a second dryer. In addition to the 34.4% energy savings, the dryer capacity was calculated to increase by 49%. The theoretical work was followed with experiments on a mixed-flow, Vertec model 6600 dryer which had been modified by placing six more tiers and a fan underneath the unit. The system was designed to allow direct recycling and use of the airwasher to supply air to the bottom six tiers. Experimental results obtained with the unmodified dryer and no air recycling or energy recovery indicated that an average of 6339 kg/h of 25.6% corn were dried to 15.6% at a specific energy consumption of 4628 kJ/kg. On the other hand, the modified dryer had a capacity of 9810 kg/h and an energy use of 3341 kJ/kg under similar drying conditions. It was estimated that the fuel savings of 27.8% would recover the $18,000 investment for the heat recovery equipment within four years. The total cost of the modification, including the additional dryer capacity, was $41,000.

3.3.6 OTHER TYPES

Sereda (1981) presented the results of a study involving the recovery of heat from a rack dryer using banks of coils filled with glycol. The exhaust from a Vertec 4500 was directed past two banks of coils (840 mm x 150 mm, 4 rows, Series 15, Type W Coils manufactured by Trane Company of Canada Ltd.). Latent and sensible heat was transferred from the exhaust to the glycol in the tubes. The glycol was then pumped to another set of coils (one 460 mm x 910 and one 610 mm x 910 mm, 4 rows, Series 15, Type W) which was ahead of the burner in the air inlet duct. Hence, the system involved air-to-glycol and glycol-to-air heat transfer, which is fundamentally less efficient than a single air-to-air heat exchanger. In addition to the

coils, 50 mm of rigid fibreglass insulation was attached to the grain drying chamber, exhaust plenum and burner unit. A limited amount of field tests were done in 1980 in which about 21 m^3 of Bonanza barley was dried continuously and a smaller quantitiy as a batch, as well as a 9 m^3 batch of Noralta flax. Energy consumption data showed a use of 3590 and 4480 kJ/kg for the continuous and batch run on barley, respectively, and 13450 kJ/kg for the flax run. The author compared these values with the 6400 and 17150 kJ/kg for barley and flax, respectively, obtained by Scott (1978) with a Vertec 2000. Although the author concluded that the energy savings were 30 to 40% over a dryer which was not insulated and was not fitted with a heat exchanger, the amount and quality of data did not warrant this conclusion. Based on the same limited data the author stated that 70% of the fuel savings appeared to be due to the inuslation and only 30% to the heat exchangers.

3.3.7 OTHER EXCHANGER SYSTEMS

Millette et al. (1986) installed a crossflow heat exchanger on a combine to use the engine heat to reduce the moisture content of grain during harvesting. Heat recovered from the combine exhaust and the cooling system was used to heat ambient air. The heated air was blown through the grain in the storage hopper. The process resulted in a temperature increase of about 10 ^{o}C for barley and wheat and 7 ^{o}C for corn; however, the moisture reduction was only 0.5 percentage points for barley and wheat and negligible for corn. It was also reported that the system did not interfere with normal combine operations during the experiments. An economic analysis based on a unit cost of $5500 and 250 ha of harvested grain showed that the heat recovery system was not economically feasible.

3.3.8 SUMMARY

1. Heat exchangers have been used successfully to reduce energy requirements in grain drying by 5 to 28%.

2. All most all studies have included direct recycling of the cooling air and the unsaturated exhaust as part of the design. Therefore, some of the reported savings were due to recycling rather than the exchanger.

3. Most commercial applications have involved air-to-air exchangers using single or multiple pass shell-and-tube or crossflow exchangers. Some laboratory-scale work was done on the use of heat pipes.

4. Fouling of the exchanger by dust and 'red dog' was not considered to be a major problem; however, most of the studies did not run long enough to warrant this conclusion.

5. The general consensus of the researchers was that the use of heat exchangers in addition to air recycling was not economically feasible.

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3.3.1 SUMMARY OF HEAT EXCHANGERS RESULTS

DRYER	EXCHANGER PASSES	AIR RECYCLING	DRYER CAPACITY (t/h)	MOISTURE CONTENT (% w.b.) INITIAL	FINAL	SPECIFIC ENERGY (kJ/kg)	SAVINGS (%)	REFERENCE
1. SHELL-AND-TUBE								
CONTINUOUS CROSSFLOW	None	Yes		29.4	16.5	5605		Winfield and Hart (1983)
	1-Pass	No		26.9	15.5	4842	14	
	3-Pass	Yes	7.6	26.2	15.0	4393	22	
CONTINUOUS CROSSFLOW	None	Yes		25.5	14.5	5486		Shifflett (1986)
	2-Pass	Yes		25.5	15.5	4460	19	
	2-Pass	Yes	2.5	26.8	15.0	4280	22	
2. CROSSFLOW								
CONTINUOUS	1-Pass	Yes	40				5	McQugan (1984)
CROSSFLOW BATCH	3-Pass	No	1.5	25.2	16.2	4655		McDonald (1985)
BATCH-IN-BIN	1-Pass	No	2.4	30	13	2580	23	Otten (1985)
RACK	2-Banks Liquid Coils			21.5	13.6[1]	3590		Sereda (1981)
				17.1	13.6[2]	4480		
				14.5	10.6[3]	13450		
2. HEAT PIPE								
BATCH (LAB.)	1-Pass			25.0	15.0	5020	8	Lai and Foster (1977)
CONTINUOUS CON-COUNTER (LAB.)	1-Pass	Yes		21.9	19.1	3855	18	Sokhansanj and Bakker-Arkema (1981)
4. DIRECT CONTACT								
RACK	air washer	Yes		25.6	15.6	3341	28	Laferriere et al., (1986)

1) Barley - continuous flow 2) barley batch 3) flax.

3.4 HEAT PUMP DRYING

3.4.0 INTRODUCTION

The heat pump is based on the reversed Carnot cycle in that it absorbs heat from a low-temperature source and rejects heat to a high-temperature sink. In the case of grain drying the source could be ambient air, a body of water, or moist air leaving the dryer. In each case the evaporator component of the heat pump absorbs heat while the compressor delivers it plus the heat equivalent of the work done on the refrigerant to the condenser. The drying air passing over the condenser picks up the heat, thus increasing its temperature and drying potential.

The use of heat pumps to dry grain is not a recent concept. As early as 1949, Davis performed a theoretical evaluation of using heat pumps in grain drying. He concluded that the heat pump could be operated on a competitve basis with other fuels for grain depths up to 0.7 m and that experimental work was needed to determine all the economic factors. In the same year, Trent (1949) wrote an article in the Farm Implement News on the future of heat pumps in agriculture.

Although heat pumps may be driven in a variety of ways, the electrically-driven heat pump has received the greatest attention because it represents an efficient replacement of the resistance heaters used in low-temperature drying systems. Because of the coefficient of performance (COP) of a heat pump, it is possible to obtain from 2 to 4 kWh of heat energy for every kWh of electrical energy consumed. For this reason the use of heat pumps has been recommended and various research projects have been sponsored by the producers of electricity. For example, Wilson (1976) respresented the Southern Iowa Electric Cooperative, Inc. at the Illinois Grain Conditioning

Conference and Strack (1984) represented the Ontario Hydro at the Electroheat Workshop. The latter mentioned that about half of the hardwood kilns in Ontario use heat pumps to dehumidify the drying air and that the same technique could be used to dry grains. Ontario Hydro has established the Industrial Electroheat Research Laboratory to assist those interested in using heat pumps or other electrotechnologies to improve productivity and efficiency.

3.4.1 EARLY WORK

In order to verify the theoretical work by Davis (1949), Flikke et al. (1957) constructed a laboratory-scale, closed system heat pump dryer. The drying bin was 1.2 m x 1.2 m and had a fully perforated floor. The heat pump was a 0.56 kW refrigerating unit using F-12 as the refrigerant. The moist air leaving the grain passed over the evaporator where it was cooled below the dewpoint and some of the water was condensed. While passing over the compressor and condenser, the air was warmed before entering the grain again. A water-cooled coil was installed ahead of the compressor to allow control of the drying air temperature. During the period of 1954-1955 various drying experiments were run with 0.3 m deep beds of oats and corn. Air temperatures of 43 to 54 °C and airflow rates of 130, 250, 365, and 470 L/s were used. Starting with an initial moisture content of about 28 and 25% (w.b.) for oats and corn, respectively, drying was stopped when a final moisture content of 12% (w.b.) was obtained. One of the observations was that large moisture gradients were present at the end of drying; in some instances these were as much as 18% percentage points. Higher airflow rates lowered the gradient. The specific energy consumption was found to vary from 1960 to 3140 kJ/kg water removed for oats and 2080 to 2810 kJ/kg from corn,

depending on the drying conditions. The authors recommended that design of larger units should be based on providing 10.5 MJ/h of refrigerating capacity for every 2.7 kg of water removed/h using an airflow rate of 150 L/s.

Although the early work showed that grain drying with a heat pump was possible, the concept was not attractive economically at that time. Therefore, the use of heat pumps was not considered again until the energy crisis in the seventies. By that time low-temperature drying (LTD) had become a popular method of drying grain corn in the United States.

3.4.2 LOW-TEMPERATURE HEAT PUMP DRYING

In many LTD systems some heat is required to raise the ambient temperature 2 to 8 °C for proper drying. In addition to using resistance heaters, solar energy, biomass fuel or hydrocarbon fuels, the temperature rise may be obtained with a heat pump. The heat pump may be used in a closed or open loop configuration. Thus, Hogan et al. (1976) designed and constructed an open-air-loop heat pump system with the assistance of the Westinghouse Electric Corporation to supply heat to a 7.3 m diameter by 4.6 m low temperature drying bin when the ambient air temperature fell below 18 °C. A thermostat stopped the 17.6 kW compressor when the the ambient temperature exceeded 24 °C or the evaporator inlet fell below 8 °C. In the latter case the pump had to be stopped to prevent frost formation on the coils. A batch drying experiment was performed with 3.3 m of corn in the bin, an airflow rate of 4250 L/s, and a heat pump output of 28.7 kW. Operating problems prevented adequate completion of the experiment and no drying data were provided.

The project was continued through 1978 after redesigning the

heat pump to avoid frost formation (Hogan et al., 1983; Foster, 1984). In addition, a duct was added to connect the top of the bin to the evaporator in order to use the moist air leaving the grain as a heat source. Normally ambient air was heated by the condenser, passed through the grain and the evaporator, and vented to the environment. However, if the ambient air conditions were such that frost would form on the coils, the control system would close the inlet and outlet dampers and open a set of recirculating dampers. A field test was run to evaluate the performance of the heat pump system and compare it with a resistance heater system under the same weather conditions in mid-October, 1978. Ninety tons of corn were dried in 17 days from 22.9 to 14.2% in the heat pump bin and in 14 days from 22.8 to 14.0% moisture content in the resistance heater bin. The difference in drying time was attributed to reduced airflow rate and the drying air recirculation to prevent evaporator frosting. The heat pump system operated in the recirculation mode for 37% of the time. The resistance system was found to require 63% more energy input.

An economic comparison of the costs of drying corn with a low-temperature system using a heat pump, resistance heater or solar energy and a batch-in-bin dryer using LP-gas or natural gas was prepared. The analysis was based on 1978 fuel prices and on projected 1988 and 1998 prices. It was determined that at 1978 fuel prices the heat pump competed favorably with the resistance heater and solar systems, but was more expensive than the LP and natural gas systems. At no time did the heat pump system compete well with natural gas.

Without providing any details, Wilson (1976) claimed that five years of experience with the use of heat pumps in low-temperature corn drying indicated that the cost of a heat pump would be recovered through energy

savings in 4 to 5 years if it is used for grain drying only.

Heat pumps have also been considered in drying of wheat and other grains, especially in Europe. For example, in Denmark, Bak (1981) reported the development of a heat pump for low-temperature drying of barley. He proposed the use of a by-pass damper in order to proportion the amount of drying air that passed over the coils of the heat pump, while the remainder of the air passed directly to the fan. The scheme was aimed at optimizing the amount of water removed from the air by the evaporator coils. Thus, as the ambient relative humidity decreased, the amount of water condensed would also decrease and more air was allowed to go directly to the fan. He concluded that the heat pump offered an energy savings of 80% but no experimental data were presented to verify this.

More recently, Brook (1986) completed a performance and economic feasibility study of the use of a heat pump in near-ambient drying of wheat in Great Britain, using weather data from 1951 to 1970 for London (Heathrow Airport), Plymouth and Elmdon. He compared the simulated performance of a 4 kW heat pump with a 4 kW and a 30 kW electrical heater, a 30 kW staged heater, no heat/normal fan, and no heat/large fan. The calculated results indicated that the specific energy consumption varied from 1900 kJ/kg for the heat pump to 2900 kJ/kg for the 30 kW electrical heater system. The corresponding energy savings varied from 10.5 % compared with an electrical heater of the same nominal power consumption to 41.3% for the 30 kW heater. However, the conclusion was that the magnitude of the operating costs savings will not be sufficient to justify the capital cost. It was also concluded that more overdrying would occur and the risk of grain damage due to mould growth would be greater with the heat pump. In fact, using a larger

fan without additional heat would provide the best drying conditions and an energy use of 2300 kJ/kg.

3.4.3 SOLAR-SUPPLEMENTED

Morrison and Shove (1977) decided to combine solar energy and a heat pump in a LTD system. It was thought that a constant drying potential of the air could be maintained by using a solar collector as the heat source during times of high insolation and supplementing the collector with a heat pump during periods of low insolation and at night. In the fall of 1975 and 1976 a 7.3 m diameter bin equipped with a 7.5 kW centrifugal fan was connected to a portable commercial solar collector (8.9 m^2) and a 17.6 kW air-to-air heat pump. The drying period ran for 34 days during which 211 m^3 of grain corn with an initial moisture content of 20.7% was dried to 15.2%. With an average daily collector efficiency of up to 60% and an average COP of 2.3 for the heat pump, the specific energy consumption was 3190 kJ/kg of water removed.

The portable collector was replaced for the 1976 study with a covered-plate and a bare-plate collector, each with an area of 26.8 m^2. In addition, the heat pump was operated using a time clock for 10 h during the night rather than using the thermostat as in 1975. On a sunny day the efficiency and total energy collected were 49.1% and 84.3 kWh and 70.9% and 121.1 kWh for the bare and covered-plate collector, respectively. The heat pump was needed for only ten nights of the 33-day drying period. The specific energy use to dry 201 m^3 of corn from 22.3 to 15.0% (w.b.) was 1780 kJ/kg, which was 44% lower than the 1975 results and 46% lower than the accepted value of 3310 kJ/kg for Illinois (Morrison and Shove, 1977).

Another solar-assisted heat pump drying experiment was conducted in

1976 by Anderson and Bern (1977). In this case a 5.5 m diameter drying bin was connected to two suspended-plate collectors and a 7.0 kW heat pump. The solar-heat pump bin and a resistance heater bin were filled with 82.5 and 77.1 t of 24% corn and was dried to 12.8 and 13.4% moisture content in 37 and 36 days, respectively. The corresponding specific energy consumption was determined to be 2030 and 2440 kJ/kg of water removed, which represented a savings of 17% for the solar-assisted heat pump system. No economic analysis was presented; however, it would appear that a 17% savings is not sufficient to offset the additional cost of collectors and heat pump.

Harrison and Allen (1980) designed a multiple-use farmstead energy unit consisting of two suspended plate solar collectors and a 10.5 kW commercial heat pump. The unit was tested with a continuous flow corn dryer. The solar collectors were found to supply about 50% of the energy while operating only 7 h of the 24 h continuous drying period.

Gupta and Allen (1980) simulated the performance of a solar supplemented heat pump system using a modified version of Thompson's deep-bed drying model. They found good agreement of the predicted results with experimental data obtained from a prototype dryer and concluded that heat pump drying was feasible in the southeastern United States. There was also a significant potential for energy savings.

3.4.4 THERMODYNAMICALLY GEARED

A thermodynamically-geared heat pump system is one in which a heat exchanger has been included in the loop. The exchanger depresses the minimum temperature to which air is cooled after leaving the dryer, thus increasing the amount of water removed from the air. In addition, the drying air is heated in the exchanger before entering the condenser thus increasing the

drying potential further.

Lai and Foster (1977) used two heat recovery methods to reclaim thermal energy from the exhaust of a laboratory-scale batch dryer. One system had a heat-pipe heat exchanger and a heat pump, and one had a heat-pipe exchanger only (see Kreith and Black (1980) for a description and principles of operation). Open-loop and a closed-loop air-circulation experiments were examined against no energy recovery tests. In each test 127 kg of corn with an intital moisture content of 20.7 to 25.6% was dried to 12.6 - 15.9% using drying air at 51.7 ^{o}C and 94 to 142 L/s. As expected, the specific energy use of the combined system was 47% lower than the heat pump only, which in turn was 7.8% lower than the no-heat recovery tests. The experimental results were also substantially higher than the simulated results. One of the conclusions was that the cost of the heat recovery equipment would exceed the cost of the dryer.

More recently, Cartwright and Hjiantoniou (1986) geared a conventional cross flow heat exchanger with a heat pump to dry unprocessed wheat grain in a laboratory dryer with a floor area of 0.14 m^2. A minimum energy use of 1320 kJ/kg of water was observed at an airflow rate of 0.13 kg/s and 100% air circulation. The range of specific energy consumption was determined to be 1320 to 1600 kJ/kg as compared with 1230 to 1500 kJ/kg obtained from theoretical simulations. The effect of gearing the heat pump was to reduce the energy input by 10% when the drying air was saturated, and 35% when the drying air left at 70% relative humidity. With the aid of the simulation program it was speculated that control of the drying airflow by speed control of the fan, rather than throttling, plus improved use of waste heat from the fan motor and addition of insulation to the exterior of the dryer would reduce the energy use to 930 kJ/kg when drying a wet product.

3.4.5 HIGH-TEMPERATURE HEAT PUMP DRYING

The work of Cartwright and Hjiantoniou (1986) was conducted at drying temperatures of about 45 °C and that of Flikke et al. (1957) at 43 to 54 °C which are above the near-ambient temperatures used in low-temperature drying but below those used in high-temperature drying.

Similarly, Hogan et al. (1981) (also see Foster, 1984) used a heat pump with a continuous flow and batch dryer operated at 40 to 50 °C, although drying temperatures up to 90 °C were considered. The heat reclaimer unit of the commercial dryer was extended to provide complete recirculation of the drying air. The average results of two batch drying tests in the fall of 1980 showed that the net specific energy consumption was 823 kJ/kg of water removed when drying 21.2% corn to 14.4% (w.b.) at 48 °C. The energy input to the compressor and fan motor was 1347 kJ/kg but about 38% of the input energy was used to increase the corn temperature while passing through the dryer. The average results of six continuous flow tests showed an energy input of 1240 kJ/kg, with 47% of the energy used to raise the corn temperature so that the energy used to evaporate moisture was calculated to be 650 kJ/kg. More batch and continuous flow tests were conducted in 1981 with corn with an initial moisture content of 27-28%; however, the wetter corn resulted in an input energy decrease of about 15%. The most serious problem with the use of the heat pump as the energy source was the significant reduction in drying capacity. Although the dryer operated at a capacity of 17,500 kg/h at a moisture reduction of 5 percentage points (25 to 20%) using the original gas heaters and no cooling of the grain in the dryer, the batch and continuous flow capacities in 1980 were only 1190 and 1630 kg/h, respectively, at a moisture content change of 5 to 6 percentage points and

no cooling. The corresponding capacities in 1981 were only 660 and 840 kg/h for the batch and continuous flow tests, respectively, while the moisture removal increased to 11 to 12 percentage points. It was concluded that the reduction in drying capacity and the high capital cost of the heat pump will not be offset by the savings in energy performance. In addition, serious frosting problem during start-up of the batch dryer led to the conclusion that heat pumps may not be suitable for batch dryers.

Peart (1982) used a 60 kW heat pump as the heat source for a continuous flow high-temperature dryer. The average specific energy use in drying grain corn was 1150 kJ/kg at a temperature of 80 °C; however, the capcity of the commercial crossflow dryer was only 2.25 m^3/h at 5% points moisture removal. Peart suggested that further energy savings could be realized by using a fossil fuel engine instead of an electric motor to drive the heat pump. Nevertheless, he concluded that heat pump drying did not appear to be economically competitive with conventional high-temperature drying.

In Germany, Kutzbach (1978a) has described a deep-bed wheat drying system with a heat pump as the heat source. He determined that the operating cost was 10% lower than for an equivalent oil heating system. Kutzbach (1978b) also modified a small batch drying plant to include a heat pump and a recirculating air system around an annular drying chamber. In drying corn from 33.5 to 14% moisture content the energy use was 33% of that with an oil-fired indirect heating system. Calculations were also presented for a larger, continuous flow dryer handling about 20 t of corn/h. He also considered the use of a diesel engine to drive the heat pump thus recovering waste heat from the engine and improving the overall performance of the dryer. In both reports Kutzbach mentioned that one of the disadvantages of the heat pump system was that the drying temperatures were restricted to 60

to 80 °C and that the capital cost of heat pump systems was too high to offset the energy savings.

Other work done in Germany on heat pumps was by Janssen (1979). He examined the principles of various heat recovery devices installed in a crossflow dryer and calculated their performance and economics. Again, the cost of installation was considered too high for heat pumps.

Much of the work done with high heat pump drying in other countries has dealt with high-temperature rice drying. For example, Kato (1982a, 1982b, 1983) has worked with heat pump drying since 1977. In one set of experiments Kato and Yamashita (1982b) modified a standard dryer to use high enthalpy exhaust air as the heat source for drying. A 2.2 kW heat pump extracted 22,120 kJ/h from 29,620 kJ/h of energy rejected from the dryer. In drying 600 kg of rough rice the specific energy consumption was determined to be 1260 kJ/kg of water removed, which was reported to be 75% less than used in a conventional rice dryer.

Gioco (1983a, 1983b) has investigated the use of heat pumps for both rice and corn drying in Italy. A heat pump was installed in an experimental dryer and operated between the air inlet and outlet of the dryer. He found that 50% of the energy present in the exhaust air was recovered and that the specific energy use was reduced by almost 50% in drying corn and rice. He outlined the application of the same heating system to farm-size dryers.

3.4.6 DEHYDROFRIGIDATION

Dehydrofrigidation involves chilling of high-moisture shelled corn to a temperature below 4 °C immediately after harvesting. At this temperature the respiration rate and microflora growth is significantly reduced, thus allowing longer drying times without grain spoilage. Shove (1968) tested the

use of a refrigiration system to dry a 412,000 kg batch of 22.6% corn in a special storage and conditioning facility constructed by the Frigidome Corp., Peoria, Ill. The facility was loaded during the period of November 3 to 19, 1965. By the middle of February, 1966, kernel damage in the form of blue-eyed mold had developed in the upper layers of the pile because the drying zone had moved only halfway through the 2.4 m high pile. At that time the grain was removed even though the average moisture content was still about 20%. No further information on the method or system is available.

In a similar application, Cunney et al. (1985) used an engine-driven heat pump to provide refrigerated storage and dry barley. Chilled air was used to prolong the storage life of undried barley, while air heated by the engine and heat pump was used to dry grain. When the heat pump was not chilling grain, exhaust air from the batch or continuous flow dryer was recycled over the evaporator to the inlet of the heating section to give higher drying temperatures and improve the efficiency. Experimental work showed that 21.5% barley could be stored for three weeks at 5 °C without deterioration and was still suitable for animal feed after 13 weeks. The heat pump system gave 10 to 15% energy savings when compared with a conventional heated air system. It was also suggested that the savings could be increased to 47-55% if an efficient diesel engine were used.

3.4.7 MODIFIED REFRIGERATION CYCLES

Foster (1984) mentioned that the use of modified refrigeration cycles involving vapour compression, air compression or a combination of the two should be considered. In mechanical vapour compression the vapour is removed from the wet product under a vacuum, and passed through a heat exchanger to recover the sensible heat and heat of vapourization. The theoretical COP of

mechanical vapour compression is 40 or more. However, Foster pointed out that this method requires an air tight bin and involves conductive heat transfer from a coil to the grain.

Iles (1980) suggested the use of the Brayton cycle heat pump for drying grain. This cycle operates at relatively low compression ratios and below atmospheric pressure.

3.4.8 SUMMARY

1. The use of heat pumps in drying grain using either a closed-loop or open-loop is technically feasible, although care must be taken to avoid frosting problems.

2. The specific energy consumption in heat pump LTD systems is significantly lower than with resistance heaters. (See Table 3.4.1).

3. Further energy reductions are possible by coupling the heat pump with a solar collector or gearing it with a heat exchanger. (See Table 3.4.1).

4. Specific energy consumption in high-temperature drying with a heat pump system is also lower than with conventional heated-air systems. (See Table 3.4.1).

5. Serious frosting problems have been encountered in high-temperature batch drying due to the warm-up period.

6. Drying capacities of high-temperature dryers have been reduced substantially by the addition of a heat pump.

7. The capital cost of installing a heat pump makes its use economically unattractive at current fuel prices. Inclusion of a solar collector or heat exchanger reduces the economic feasibility further.

8. The amount of investment charged to drying may be reduced by making the heat pump movable and using it for other heating purposes during the remainder of the year.

9. Replacing the electric drives on compressors with internal combustion engines will provide greater thermal efficiencies, reduce the power demand on electrical services, and allow higher drying temperatures.

10. Use of modified refrigeration cycles has been suggested but no experimental work has been done.

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TABLE 3.4.1 SUMMARY OF HEAT PUMP DRYING DATA

DRYER	FAN (kW)	COMPRESSOR (kW)	HEATER (kW)	COLLECTOR (m^2)	AIRFLOW (m^3/s)	SYSTEM COP	TEMP. (°C)	SPECIFIC ENERGY (kJ/kg)	MATERIAL	REFERENCES
THEORETICAL SIMULATION										
LTD		4	N/A	N/A	5.0g				WHEAT	Brook
		N/A	30	N/A	5.0		+5[a]	2900	WHEAT	(1986)
		N/A	N/A	N/A	6.0			2300	WHEAT	
LABORATORY OR PILOT SCALE										
HTD-batch	0.37	0.56	N/A	N/A	0.13-0.47		43-54	2080-2810	CORN	Flikke et al.,
	0.37	0.56	N/A	N/A	0.13-0.47		43-54	1960-3140	OATS	(1957)
HTD-batch	0.37	0.56	heat pipe	N/A	0.14	3	51.7	2880	CORN	Lai and Foster
	0.37	N/A	heat pipe	N/A	0.14		51.7	4790	CORN	(1977)
	0.37	N/A	N/A	N/A	0.14		51.7	5330	CORN	
HTD-batch		1.8	crossflow exchange	N/A	0.14	4.6[b]	45	1320-1600	WHEAT	Cartwright and Hjiantoniou (1986)
COMMERCIAL SCALE										
LTD	7.5	17.6	N/A	N/A	3.98	4.8[b]	+7.2[a]	2010	CORN	Hogan et al.
	7.5	N/A	24	N/A	4.69	1	+5.2[a]	3260	CORN	(1983)
LTD	7.5	17.6	N/A	8.9	4.48	2.3	+4 to 5[a]	3190	CORN	Morrison and
	7.5	17.6	N/A	53.6	4.48	2.3	+4.6 [a]	1780	CORN	Shove (1977)
LTD	3.7	7.0	N/A	23.8	1.97	2.4		2030	CORN	Anderson
	3.7	N/A	2.4	N/A	1.98	1		2440	CORN	and Bern (1977)
HTD-batch	11.1	4.5	N/A	N/A		4-5[b]	48	1347	CORN	Hogan et al.
HTD-continuous	11.1	4.5	N/A	N/A		4-5[b]	48	1240	CORN	(1981)
HTD-continuous		4.5	N/A	N/A			80	1150	CORN	Peart (1982)
HTD-batch		2.2	N/A	N/A				1260	RICE	Kato and Yamashita (1982)

N/A - not applicable a) + indicates temperture rise above ambient b) based on heat transferred from refrigerant to drying air.

4.0 ALTERNATIVE ENERGY SOURCES

4.1 INTRODUCTION

Conventional artificial drying systems use large amounts of fossil fuels. At a time of supposedly dwindling supplies and increased fuel prices, attempts have been made to replace fossil fuels with renewable ones. The two main alternative energy sources considered for grain drying are solar and biomass. Aside from being renewable energy sources, both are independent of the operation of multinational fuel companies and the manipulations of foreign governments. The use of solar energy in grain drying was discussed in the section dealing with low-temperature drying; however, the treatment was restricted to solar systems used in Canada. Solar energy was also discussed in relation to desiccant regeneration and heat pump applications. These topics will not be considered again. Instead, the following review will provide a more general picture of the work done to implement solar drying in the United States and elsewhere but will not consider crops other than grain corn. A review of solar drying of various crops in developing countries was presented by Bansal and Garg (1987) and Lawand (1975). Spenser and Graham (1987) considered the development of solar drying of cereal grains and hay in Scotland. There are various ways of using biomass to dry grain. One of these is to convert biomass into liquid or gaseous fuels, such as ethanol or methane. However, the processes are relatively complex and costly and are not economically compatible with the short drying seasons. The review will therefore only consider those processes specifically developed for grain drying.

4.2 SOLAR ENERGY

4.2.1 INTRODUCTION

Although solar energy is our most abundant permanent source of energy, it arrives at the earth's atmosphere in a dilute form (about 1.36 kW/m^2) and is further attenuated while passing through the atmosphere. As a result the average solar radiation that strikes the earth's surface is about 310 to 620 W/m^2; however, the amount at any particular area may be considerably smaller depending upon the geographic location, season, weather conditions, and degree of pollution. The dilution of solar energy requires relatively large systems to convert the energy into heat for use in practical heating systems.

Conversion of solar energy into heat is accomplished with solar collectors which consist of a surface that absorbs radiation. The corresponding increase in internal energy results in a temperature rise of the absorbing material. Removal of part of the absorbed energy is done by heating a fluid which is brought into contact with the material. Solar collectors fall into two basic classes: concentrating and nonconcentrating. Concentrating collectors have a large area to redirect the intercepted direct or beam radiation to a small absorbing area. This arrangements allows for high operating temperatures and collector efficiencies; however, the construction cost is also high. In contrast, nonconcentrating or flat-plate collectors are relatively simple in design and inexpensive. Heat losses to the environment is a limiting factor in obtaining high efficiencies but flat-plate collectors are more useful in absorbing diffuse radiation. In order to reduce heat losses, one or more transparent cover plates are used and the backside of the collector is insulated.

There is a large body of information on the design, construction and operation of solar collectors and the fundamentals of solar radiation in various journals and books. Much of the basic and applied research of the use of solar energy is found in those publications; one excellent source being "Solar Energy", which is the Journal of Solar Energy Science and Technology of the International Solar Energy Society. Since the present review is restricted to the use of solar energy in grain drying, most of the references are found in the agricultural engineering publications.

The use of solar energy in artificial crop drying was suggested by various researchers long before the energy crisis of the seventies (Buelow, 1958; Lipper and Davis, 1960). Later Sobel and Buelow (1963) designed and tested a "no-glass" collector that could be incorporated into the roof construction of farm buildings.

4.2.2 HIGH-TEMPERATURE DRYING

Although there have been a few reports of the construction or plans to construct large collector fields suitable for high-temperature grain drying, no information was found on their performance. For example, Gold Kist, Inc. was said to be building a 1170 m^2 solar field to supply heat for grain dryers at its Decatur, Ala., soybean-processing plant. The field was expected to result in energy savings of 160,000 L of fuel (Gogerty, 1978). Carnegie and Pohl (1980) described the construction of a large solar crop dehydration systems at Fresno, California. The system was designed to supply 70% of the total heat requirements of a single tunnel dehydrator during a 200-day operating season. Drying temperatures of 50 ^{o}C at airflow rates of 9.4 m^3/s were expected in November. These conditions were considered suitable for the final dehydration of raisins. No experimental drying data

were found of either of the above systems; however, Carnegie (1984) did report on the operation and required maintenance of the 1980 m^2 collector-rock storage-heat wheel recovery system at Fresno for the period of 1978 to 1984. Among other data, he reported the annual repair costs to be a little over 1% of the installation cost. He also calculated the energy cost to be $7.58/GJ.

Loewer et al. (1981) used computer simulations to investigate the use of a concentrating collector with a rock storage unit to provide heat for high-temperature drying. They assumed that the collector would be operated several weeks before the harvest in order to store enough energy in the rocks to dry the entire crop. The analysis indicated that high-temperature solar grain drying was not economically competitive with propane until the cost of the fuel would increase by a factor of 2 to 3 or large tax credits and low interest rates be made available for solar drying systems.

Similarly, Misra et al. (1982) simulated the storage of solar energy in a solar water pond and underground in soil during the summer and use of the stored heat to dry grain at temperatures > 50 °C. They calculated that the overall efficiency of collection to utilization was 10 to 20% and concluded that the system was not economically feasible.

4.2.3 LOW-TEMPERATURE DRYING

Because low-temperature drying involves heating the drying air a few degrees above ambient, it is uniquely suited to the use of solar energy. It is therefore not surprising that since the mid-seventies a flood of research reports and papers have been published on this topic. In addition, there are a number of publications dealing with on-farm demonstration projects; for examples see Baker and Shove (1977), Peterson (1980), Morrison and Peterson

(1982), DeBusk (1983) and Lambert and Harner, 1983. Some agricultural engineering extension services in the United States provide plans of solar collectors systems; for example, the University of Illinois has eight sets of plans ranging from roof collectors to portable units.

The availability of solar energy at a particular geographic location depends on the latitude, the time of day and year, and the local weather conditions. Furthermore, the ability to convert solar energy into heat depends on the collector design, which may vary from simple do-it-yourself to complex manufactured units. The above factors have resulted in a wide diversity of opinion about the usefulness of solar energy in low-temperature grain drying. The following sampling of the literature will attempt to bring out the various results.

a) Bare-plate collectors

The simplest of all collector designs is the bare-plate collector. It usually consists of a metal absorber without cover plates and a provision for air to flow past the underside of the plate. A metal roof with air flowing through the space between the rafters and some material fastened to the bottom of the rafters is an example of a simple bare-plate collector. The same design can be used for metal walls or a free-standing collector. As with all collectors, the main factors to consider in this type of structure are those relating duct size and airflow rates to heat transfer to the air passing underneath the absorber plate. The main variables affecting the configuration of the duct are pressure drop and heat loss. Pressure drop is of importance in considering the fan size for operating the system, while heat loss determines the efficiency of energy transfer. An air velocity of 3 to 7 m/s past the absorber plate and a collector pressure drop of 12 mm of

water column should provide suitable operating conditions for solar-assisted grain drying.

Bare-plate collectors have been studied by Sobel and Buelow (1963), Bauman et al. (1975), Morrison and Shove (1975), Peterson (1977) and Bauman and Finner (1979). Morrison and Shove (1975) used a metal bare-plate collector installed as a secondary wall on the south-side of a low-temperature drying bin. Bauman and Finner (1979) used the heat collected of a galvanized metal roof and claimed to have obtained energy and cost savings of 50% in low-temperature drying of grain in Wisconsin.

Malik and Puri (1977) did a general analysis of the thermal performance of a bare-plate collector and derived heat transfer relationships for various insolation levels and wind speeds. Their simulation results indicated that temperature rises of 1 to 2 ^{o}C is possible at insolation levels of 631 to 1104 W/m^2 and airflow rates suitable for low-temperature drying. The above researchers and others found that bare-plate collectors are the least expensive but also have a relatively low collection efficiency. The amount of solar energy converted into useful heat with a bare-plate collector has been determined to be in the range of 15 to 30%, depending upon the prevailing conditions.

b) Covered-plate collectors

Covered-plate collectors are basically the same as bare-plate ones with the exception that one or more transparent layers of material cover the absorber plate. The cover plate reduces the heat loss due to forced and free convection from the absorbing surface. Suitable cover materials include plastic films, fluorocarbons, acrylics, fibreglass, carbonates and glass. In general the plastic films are the least expensive and durable, while glass

is the most expensive and durable. A summary of the properties of some of the common cover plate materials is found in Table 4.2.1. Covered-plate collectors can also be built into the roof and walls of buildings, wrapped-around grain bins or made free-standing. In the case of new buildings, the roof can be made of clear, fibreglass-reinforced plastic to act as a cover and the attic painted black to act as the absorber. Or an absorbing surface could be fastened to the underside of the rafters. In either case the air flows between the cover plate and the absorber, while the backside of the absorber may be insulated. However the high airflow rates used in grain drying essentially eliminate the need for insulation.

Experimental studies involving covered-plate collectors on roofs or walls have been reported by Smit and Shove (1976), Morrison and Shove (1975), Hansen and Smith (1977), McLendon and Allison (1978), Converse et al. (1978) and Krishnan et al. (1980). The collection efficiencies varied greatly but were found to be in the range of 30 to 50% under favourable conditions. While some authors concluded that the use of covered-plate collectors was not economically justified in grain drying, others determined it to be less expensive than ambient air drying. The diversity of opinions is partly due to the limited data on which the conclusions were based; in some instances, only one year of results were considered. In addition, many investigators used different investment credits, solar credits and other economic assumptions in calculating the cost of solar drying.

General work with covered-plate collectors has shown that for a temperature rise of the order of 10 ^{o}C, the performance of an air heater is essentially independent of the number of cover plates (Goodman and Menke, 1975). Therefore, for low-temperature drying applications one cover plate should be sufficient.

c) Suspended-plate collectors.

Suspended-plate collectors are similar to covered-plate ones except that the air flows on both sides of the absorber plate. Rankine and Charters (1969) and Charters et al. (1972) have compared the performance of suspended-plate collectors with covered-plate ones in which the air flowed either above or below the absorber plate. They concluded that the heat loss is always the greatest in the collector with the air flowing over the absorber plate only. Other studies dealing with suspended plate collectors have been reported by Williams et al. (1976), Peterson (1977), Kline (1977), and Converse et al. (1978, 1982).

Since the suspended-plate units have lower heat losses, they have a higher collection efficiency (40 to 60%). The collectors are however more expensive to construct and are generally considered uneconomical for grain drying applications.

d) Plastic bag collectors

These units basically consist of a large plastic bag inflated with the drying air. The bags are usually placed on the ground but could also be installed on a building or bin wall. In some instances the upper part of the bag is made of clear polyethylene and the lower part of black polyethylene. Plastic bags made of polymethyl-methacrylate, polycarbonate, fibreglass reinforced polyester, polyvinyl fluoride and polyvinyl chloride have also been used. The performance of the collector depends upon its design, shape and curvature. For example, the amount of incident radiation depends on the curvature of the air supported cover, while the shape and position of the absorber determines the amount of absorbed radiation. As a result, various designs have been used in solar-assisted grain drying. The

six basic configurations are (Keener et al. (1977)):

(i) curved cover, flat absorber
(ii) curved cover, tubular absorber
(iii) curved cover, curved absorber
(vi) triangular cover, flat absorber
(v) concentric tubular cover and absorber
(vi) eccentric tubular cover and absorber

Some designs included multiple channels for airflow (Meyer et al.(1975) and porous absorber plates (Chau et al. (1980) and Bansal et al.(1982)).

Experimental results of the use of bag collectors have been presented by Meyer et al.(1975), Morey et al. (1975), Hammond and Winsett (1976), Williams et al.(1976), Lipper and Welker (1977), Misra et al.(1979) and Bansal et al. (1982). Analytical analyses using computer simulations were reported by Meyer et al. (1976). Most of the experimental work dealt with low-temperature drying so that the average temperature increases were limited to 2 to 5 ^{o}C but under certain conditions rises of up to 35 ^{o}C were observed. Collection efficiencies varied from 30 to 60%.

Although bag collectors were found to be relatively inexpensive, especially those constructed locally and resulted in significant energy savings, nearly all researchers concluded that they were not economically attractive. In addition, serious operational problems with snow and wind loading, stress cracking of covers during freezing weather, and mechanical damage were reported. Some investigators also commented on the inconvenience and cost of installation and removal of the large collectors (up to 90 m^2 in some studies) at the beginning and end of each drying season.

4.2.4 SIMULATION STUDIES

The use of solar energy in low-temperature grain drying is greatly dependent upon the location and a variety of other factors. Although

experimental work is necessary to evaluate the feasibility of solar-assisted drying, the amount of data that can be collected in any one year is limited. Therefore, many investigators have developed mathematical models to describe solar-assisted low-temperature drying of grain. In most instances the models were validated with field data before they were used to evaluate the performance of the system under a range of weather conditions and operating procedures.

Meyer et al. (1976), Pierce and Thompson (1978a, 1978b, 1979), Sabbah et al. (1977), Peart (1977), Bakker-Arkema et al. (1977), Kline and Odekirk (1978), Colliver et al. (1978), Morey et al. (1979), Morey and Cloud (1977), Broder et al. (1979), Heid and Aldis (1981), Polak et al. (1981), and Pitts et al. (1982) have performed simulation studies. The various studies considered such low-temperature drying factors as airflow rate, initial moisture content, harvest date, and yearly weather data coupled with the use of no-heat, continuous heat or intermittent solar heat. Some investigators have also considered the effect of various fan management strategies on the drying process, while others concentrated on the performance of different collector configurations.

Since airflow rate is the most important parameter in the design of low-temperature drying systems, most simulation studies have dealt with the determination of the minimum airflow rate at which grain will dry without deterioration under different drying conditions. As expected, the conclusions vary greatly and there is no one airflow rate that is optimal for low-temperature drying systems. For each location the required airflow rate and the allowable temperature rise have been shown to depend on the intitial moisture content, weather, and harvest date. For example, Pierce and Thompson (1978a) found that solar heat resulted in a significant

reduction in airflow rate requirement in Indianapolis, Indiana and Mansfield, Ohio but not in central Iowa. On the other hand, Loewer et al. (1981) stated that the temperature increase due to solar heating would increase the probability of obtaining unacceptable levels of grain corn deterioration. They recommended that low-temperature drying is not suitable for Kentucky conditions and that applications of solar energy would have to be in high-temperature drying systems.

Simulation studies have also shown that energy requirements with solar supplemented systems was lower than for systems using continuous heat; however, the overall drying costs were highest with solar systems. In addition it was found that overdrying was a major problem with the addition of supplemental heat. Therefore, simulation studies were also conducted to determine different operating procedures and management schemes. For example, Pierce and Thompson (1978b) investigated layer drying, airflow reversal, recycling and stirring as possible solutions to overdrying. They concluded that stirring was the only management technique that did not adversely affect drying performance. Baker et al. (1979) confirmed that continuous stirring did produce a fairly uniform moisture distribution in solar-assisted low-temperature drying of grain corn.

Many simulation studies resulted in the conclusion that low-temperature drying with or without solar energy would benefit from the use of an automatic control system. Wilcke et al. (1979) and Harrell et al. (1979) are among those who worked on the development and testing of computer-based control systems for solar drying. It appears that control systems will reduce the energy consumption and thus make more efficient use of solar energy. In addition, they reduce the amount of management required but at a higher

drying cost.

4.2.5 CONCENTRATING COLLECTORS

Although the use of flat-plate collectors has generally been found not to be cost effective in grain drying, some researchers did considered the more expensive concentrating types. Thus, Parker et al. (1977) and Polak et al. (1981) discussed and modeled the potential of using concentrating collectors, while Hellickson et al. (1981) performed field tests with a dual-sided, trapezoidal shaped collector which was designed to intercept insolation directly on the south side and indirectly from a parabolic trough reflector on the north side. During the drying experiments they observed average collector efficiencies of only 39%, which was much lower than expected. They contributed the disappointing results to irregularities of the reflector surface. Hellevang and Hellickson (1979) also experimented with a concentrating collector system for grain drying.

In order to make full use of concentrating collectors, it is necessary to be able to track the sun (Parker et al., 1977); however, this increases the cost of the system considerably. Since most researchers have concluded that solar drying with flat-plate collectors is not cost effective, it is not surprising that concentrating collectors are even less economical.

4.2.6 HEAT STORAGE

As mentioned above, solar energy is an intermittent source of heat and many researchers have worked on methods to store solar energy during periods of excess. It has been shown that solar energy can be stored as sensible, latent or thermochemical energy and that each method differs in the amount of heat that can be stored per unit amount of storage material. Both sensible and latent heat storage in the temperature range of 20 to 80 °C are

of interest for water and space heating, and high and low-temperature drying of grain. The use of latent heat storage with grain drying systems was discussed by McCracken 1977). A general review of latent heat storage systems was prepared by Pal and Otten (1986).

Since most grain is dried in the fall when the availability of solar energy is limited and intermittent, some researchers have evaluated long and short term energy storage. Short term storage involves storing of excess solar energy during the day for use during the night. This type of storage is inherent in the low-temperature drying process because excess solar energy causes overdrying of corn in the bottom layers during the day. The overdried corn will act as desiccant during the night and lower the humidity of the drying air so that drying of wet corn will continue. Short term storage can also be designed into the collector system. Aside from using rocks or other materials to store thermal energy as sensible or latent heat (DesChenes et al., 1976; Eckhoff and Okos, 1977, 1978; Hansen and Smith, 1977), one system of considerable interest in agriculture has been the Trombe wall. The Trombe wall collector is a flat-plate system in which one or more cover plates are placed on the surface of a block wall. The blocks are usually painted black and act as the absorber plate. The wall is constructed to allow heated air to flow through gaps between the blocks. The blocks store heat during periods of high insolation and release it at other times. The result is a damping of the temperature fluctuation which some investigators believe to be beneficial for low-temperature drying. Because of the need of a large block wall, the Trombe system has been most popular for space heating of animal housing with grain drying being a secondary use (for example, see Otten et al., 1983; Kocher et al., 1981).

The general opinion is that the addition of solar energy storage systems for grain drying further reduces the possibility of making solar energy economically viable in grain drying.

4.2.7 SUMMARY

1. Solar energy is generally not suitable for high-speed, high-temperature drying because

a) solar energy is an intermittent source;

b) the collector surface needed to supply all the heat for even a small high-temperature dryer is unrealistically large; and,

c) non-concentrating collectors cannot provide the large temperature rise required.

2. Preheating of the drying air for high-temperature dryers is possible if a large collector is already available for other applications; such as, warming of livestock buildings.

3. Solar energy may be used effectively in low-temperature drying. Simple collectors may be used to raise the temperature and reduce the relative humidity of the drying air sufficiently since the drying process is a slow one. For the same reason, solar energy can also be used for the low-temperature phase of combination drying.

4. The intermittant charateristic of solar energy is not a problem in low-temperature drying because the grain is able to tolerate different drying rates. Furthermore, excess energy is stored in the form of overdried grain which at night will reduce the relative humidity of the drying air so that drying will continue. Hence, the grain acts as a solar heat storage.

5. Collection of solar energy requires a high capital investment which cannot be justified on the basis of fuel savings alone. Use of solar energy

must therefore have multiple applications, such as space heating and drying.

6. There is no one airflow rate that is optimal for low-temperature drying. The airflow rate and allowable temperature rise are completely dependent on the location and harvest conditions. In some instances use of solar energy will result in an increased chance of spoiling grain corn before it can be dried.

7. Use of energy storage with collectors increases the drying cost and makes the use of solar energy even less attractive.

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TABLE 4.2.1 A SUMMARY OF PROPERTIES OF SOME COMMON COVER PLATE MATERIALS

Material Name	Temperature Limits (°C)	Weatherability (comment)	Chemical Resistance (comment)
Lexan (Polycarbonate)	120°-130° Service Temperature	Good: 2 yrs. exposure in Florida caused yellowing	Good: Comparable to Acrylic
Plexiglass (Acrylic)	80°-90° Service Temperature	Average to Good: Based upon 20 yrs. testing in Arizona, Florida, and Pennsylvania	Good to Excellent: Resists most acids and alkalis
Teflon F.E.P. (Fluorocarbon)	200° continuous use 245° short term	Good to Excellent: Based on 15 yrs. exposure in Florida environment	Excellent: Chemically inert
Tedlar P.V.F. (Fluorocarbon)	105° continuous use 175° short term	Good to Excellent: 10 yrs. exposure in Florida with slight yellowing	Excellent: Chemically inert
Mylar (Polyester)	150° continuous use 200° short term	Poor: Ultraviolet degradation great	Good to Excellent Comparable to Tedlar
Sunlite (Fibreglass)	90° continuous use	Fair to Good: Regular (7 yrs. solar life). Premium (20 yrs. solar life)	Good: Inert to chemical atmospheres
Temper Glass (Glass)	230°-260° continuous 260°-290° short term	Excellent: Time Proven	Good to Excellent: Time Proven
Clear Lime Sheet Glass (Low Iron Oxide Glass)	200° for continuous operation	Excellent: Time Proven	Good to excellent: Time Proven
Clear Lime Temper Glass (Low Iron Oxide Glass)	200° for continuous operation	Excellent: Time Proven	Good to excellent: Time Proven
Sunadex White Crystal Glass (.01% Iron Oxide Glass)	200° for continuous operation	Excellent: Time Proven	Good to Excellent: Time Proven

Source: Ratzel and Bannerot (1977)

4.3 BIOMASS TO DRY CROPS

4.3.1 INTRODUCTION

Although the term biomass includes the total organic matter produced by plants, for energy production purposes it is usually limited to above the ground or harvestable portions of the plant. Wood is an obvious source of biomass but crop residues are another source. There are a number of biological or wet processes to convert biomass and organic residue to liquid or gaseous fuels. For example, both ethanol and methane production require biological reactions in aqueous solutions. Such processes are generally not compatible with the short-term demands of grain drying because they require larger capital investment and become only cost effective with continuous production on a large scale.

There are, however, several dry processes to convert biomass directly to heat or other fuels. One way of classifying dry processes is presented in Figure 4.3.1 (Otten, 1981).

Hydrocarbonization is a physico-chemical conversion process which produces fuel oils or gases by subjecting organic material to high temperatures and pressures. Hydrogasification is an advanced technology which has been tested commercially for converting coal to pipeline gas. The process involves feeding organic matter, hydrogen and steam into a reactor at 500°C and 70 atm. The result is a low calorific gas which can be further processed to give 95 to 98% methane. Hydrogenation and carboxylolysis yield a low sulphur fuel oil similar to No. 6 oil with a heating value varying between 30 and 35 MJ/kg, by contacting the organic matter with carbon monoxide. The basic reaction technology was first developed by the U.S. Bureau of Mines, which has since experimented successfully with a variety of organic feedstocks including crop wastes, manure, wood, urban refuse and

sewage sludge. Carboxylolysis differs slightly from hydrogenation in that carboxylolysis uses steam and a catalyst, sodium carbonate, to reduce the organic feed stock; while hydrogenation requires hydrogen. The temperature range of 250 to 400°C and pressure range of 100 to 275 atm. are respectively lower and higher than in hydrogasification. It has been estimated that about 2 barrels of oil are produced per tonne of dry organic matter.

Pyrolysis involves the physical and chemical decomposition of organic matter by the action of heat in the absence of oxygen. Depending on the reactor temperature (usually 500 - 1100°C), pressure (usually atmospheric) and length of treatment, the end products include varying amounts of gas, liquid and solid char fuels. The synthesis gas portion consists primarily of methane, hydrogen, carbon monoxide and carbon dioxide and it may have a calorific value as high as 32 MJ/m^3. There have been a number of studies reporting that pyrolytic conversion of animal manure to fuel gas is presently economically unfeasible, presumable due to the high moisture content of manure.

Combustion is a process in which biomass is burned in the presence of air. It may be further subdivided into gasification, incineration and direct combustion, depending on the amount of air used. Thus, gasification or partial combustion is the thermal decomposition of organic matter in the presence of water (steam) and a limited supply of air to produce mainly hydrogen and carbon monoxide with smaller amounts of methane. Reactions are carried out in packed beds at temperature above 1100°C. The resulting gas mixture, which is commonly known as producer gas, has a low calorific content of 4 to 6 MJ/m^3. Direct combustion of biomass has rarely achieved an efficiency greater than 65% in the past. However, recently furnaces have

become commercially available with combustion efficiencies exceeding 80%. In a properly designed furnace burning of the fuel occurs in the primary combustion chamber with further burning of the volatile gases occuring in the secondary combustion chamber. Air should be supplied from beneath the solid fuel as well as overfire air to ensure combustion of the volatile gases above the fuel.

It has been suggested that biomass may become a significant factor in the total energy picture of a country. Certainly, in China, where nearly 32% (7.7 EJ) of the total energy needs are derived from crop residues and fire wood (Jin et al., 1983), this is already true. In contrast only 4% of the U.S. energy needs are in the form of biomass energy, including wood (Klass, 1978); however, various studies have been performed to evaluate the use of biomass for large scale energy production (Jenkins et al., 1984 ,1985). In fact, in California power plants with about 350 MW generating capacity using biomass fuels are either operational or under construction (Tuvell et al., 1985; Anon, 1984). Similar developments were reported to be in progress in other locations by Sargent et al. (1983), Mason et al. (1983) and Parnell et al. (1983). However, in all those cases the biomass was available as processing waste at a specific site and often presented a disposal problem. On the other hand, agricultural residues are distributed resources which must be collected and transported to the energy plant. Some researchers have discussed the research needs and priorities to further the use of agricultural residues as a energy source in small and large scale operations in the United States (Fipps and Dietrich, 1981; Jenkins and Sumner, 1985).

Agricultural residues have also been considered in the development of Third World countries which are frequently unable to import sufficient crude oil for domestic requirements. For example, Onaji et al. (1980) examined

the economic feasibility of gasification of renewable resources in Nigeria, and Groeneveld and Westerterp (1980) did the same for Tanzania.

In view of the extensive scope of the use of biomass as an energy source and the terms of reference of this study, it was decided to concentrate only on the use of crop residues to dry grain.

4.3.2. BIOMASS AVAILABILITY IN ONTARIO

The most abundant and inexpensive source of agricultural biomass for the Ontario farmer is crop residue, such as straw, stover and corn cobs. In Table 4.3.1. the average amount of straw and stover produced in each district of Ontario and six Ontario counties is summarized. Obviously, Southern and Western Ontario have significant quantities of crop residue; however, the question is "How much of a total crop can be removed without increasing soil losses or reducing the soil's productivity?"

It is well-known that crop residues provide organic matter needed by the soil. Soil organic matter prevents erosion, promotes water infiltration and efficient water usage, and acts as a buffer and source of nutrients. It also plays an important part in soil aggregation, tilth maintenance and cation exchange capacity. Posseluis and Stout (1980) presented a method of estimating the quantity of residue that could safely be removed while providing sufficient soil erosion control and productivity capacity. Similarly, Heid (1984) estimated the amount of crop residue that could be removed from the Great U.S. Plains without significant losses from wind or water erosion. The results of various studies have suggested that as a general rule less than half of the straw and stover may be collected without affecting most soils. Actually, the work by Richey et al. (1982) suggests that collection of corn stover by baling or stacking following windrowing would result in

the recovery of only 50% of the windrowed material. In other words, the efficiency of current collection systems ensures that sufficient material is left to maintain soil integrity.

In contrast with the U.S. Plains situation, recent studies for Western Canada have concluded that virtually all of the wheat straw should be left on the land (Canadian Resourcecon Limited, 1985). The total surplus wheat straw production in the prairie provinces was placed at about 181,000 t annually.

Although crop residues are available in some areas in large quantities, there are handling, storage, transport and systems problems which must be considered by the user. In fact, most of the cost of this energy source is handling cost.

4.3.3 BIOMASS PROPERTIES

Biomass properties are important in the design of the delivery and conversion systems. One of the critical factors for collection, processing, transportation and storage of biomass is moisture content. At harvest, cereal straws may have a moisture content of only 10 to 20% (w.b.) and can generally be field dried if the moisture content is too high for storage. Field drying of straw has been modeled and tested against field data by Jenkins et al. (1984, 1985). High moisture contents will not only result in excessive spoilage but also in some instances in spontaneous combustion. In contrast, corn residue often has moisture contents in the range of 30 to 50% (w.b.) and is therefore difficult to keep from being spoiled in storage.

Another important parameter is the bulk density of the material. Not only are the handling and transportation systems affected by the bulk density but also the conversion equipment. Since the bulk density of crop

residues is generally low, various methods of packing have been investigated. Reed and Bryant (1978) described a number of biomass densification processes and included cost estimates and energy balances. A general overview of densification technology for agricultural residues was presented by Smith et al. (1983). Experimental results of cubing ryegrass, corn cobs, corn husks, and bermuda grass, and pelleting of wheat straw were presented by Hellwig et al. (1984). They confirmed the observations of Williams et al. (1978) and others that the cuber produced poor cubes. Other researchers, such as Dobie and Carnegie (1973), looked at the use of binders to improve the quality of the cubes. Ammonium lignin sulfonate, starch and whey have been used as binders. Ammonium lignin sulfonate proved to be a good binding agent in producing cubes of wheat straw. Sachs et al. (1985) determined the flow properties of densified biomass and found them to be superior than those of loose materials.

The design of energy from crop residue systems also requires knowledge of the heating value or calorific content, which is expressed in MJ/kg. The heating values reported in the literature are either higher heating values (HHV) or lower heating values (LHV) on a wet or dry basis. The HHV is a measure of the total available energy, including the heat recovered upon condensation of the combustion water vapour. On the other hand, the LHV does not include the heat of condensation.

A fourth parameter of interest is the ash content. High ash content materials increase the abrasion wear of the harvesting and handling equipment, and increase the emission rates from the burners. Collection and handling equipment may increase the ash content through the addition of soil and foreign material. The ash content of agricultural residues varies

considerably (Osman and Goss, 1983; Kumar et al., 1984; Rossi, 1984; Ebeling and Jenkins, 1985).

Loewer et al. (1982a) performed an engineering analysis of biomass energy availability and concluded that sufficient energy exists in corn residue and grain to dry corn. More specifically, they found that drying corn from 30.5 to 15.5% moisture (w.b.) requires either 86.3% of the cobs, 26.4% of the stover or 13.8% of the grain. The cost analysis showed that both cobs and stover were competitive with propane in 1980 as a source of energy for grain drying, with cobs being the better choice. Grain was not competitive because of its market value at that time. Further results were given by Loewer et al. (1982b).

Strehler (1979, 1981) considered some of the charateristics of straw in relation to direct combustion; including volatiles, chemical analyses, and demand for combustion air. Saxena and Buchanan (1982) performed Parr calorimeter experiments to determine the HHV and LHV of a variety of agricultural residues. Oat straw had the lowest heat content and a mixture of sunflower hulls and pulp the highest. Most crop residues had little or no available heat when the moisture content was greater than 50% (w.b.).

Ebeling and Jenkins (1984) reviewed various standard laboratory procedures of determining the higher heating value, moisture content, proximate, ultimate, and ash analysis of biomass materials. In a subsequent publication Ebeling and Jenkins (1985) presented the higher and lower heating values and proximate fuel analyses of 62 biomass materials obtained from crop residues, orchard prunings, vineyard prunings, food and fiber wastes, forest residues, and energy crops. The field crop results, which have been reproduced in Table 4.3.2., show that the energy content of cereal grain straw, stover, and cobs is approximately the same. In fact, higher

heating values of all biomass samples were found to lie in a narrow range when expressed on a dry, ash free basis.

Table 4.3.3 contains higher heating values of crop residues as a function of moisture content. The decrease in energy content with an increase in moisture is due to the need to evaporate larger quantities of water. If the feedstock is too wet, more heat would be required to evaporate the water than is contained in the dry matter. For this reason Nelson and Loehr (1975) decided that animal manure was an inappropriate fuel for on-farm use.

Bjornstad et al. (1984) used a linear programming model to analyze the cost competitiveness of biomass fuels in agricultural applications, including liquid fuels, for the projected year 1990. They concluded that without major disruptions in energy markets biomass fuels would in general not become cost competitive by 1990; however, fuel oil, natural gas and propane used in grain drying and space heating applications could already be replaced with crop residues or wood at cost savings.

4.3.4 CEREAL GRAIN STRAW

The relatively low bulk density of loose cereal grain straw may be increased using one of the packing techniques listed in Table 4.3.4. From a delivery and combustion point of view pellets are the most desirable form but the energy requirements for pelletizing straw are excessive and the machinery costly. For on-farm combustion the square and round bales are considered to be the most convenient form, especially as the equipment is readily available. One disadvantage of large bales is that they must be fed intermittently into the furnace, which makes it difficult to operate the furnace at a steady output. Some of the problems of compacting straw were

discussed by LaRue and Pratt (1977).

Storage of wheat and rye straw, as well as stover, in large round bales in Georgia was studied by Sumner et al. (1984). They found that the apparent moisture content and mass of bales without covers were highly influenced by rainfall during the fifteen month storage period. Bales covered at the top with polyethylene sheets did not show excessive moisture increase due to rain. Furthermore, bales stored on well-drained sod appeared to have very little moisture absorption through the bottom of the bales. Placing wheat straw bales on elevated beds or timbers resulted in no change in mass and moisture content when compared to storage on grass sod. Bales sprayed with either asphalt, motor oil, or tar showed a rapid increase in mass and moisture content. These materials were no more effective in reducing rain penetration than the check bales without covers.

Peill (1980) had observed similar results in Nova Scotia; that is, straw stored outside readily wetted to the point where burning became very difficult and little useful heat was obtained. Straw stored under cover remained in excellent condition, even under the most adverse weather conditions.

These observations are similar to those reported by researchers working with the storage of hay packed in large round bales (Verma et al., 1978; Rider et al., 1979; Lechtenberg et al., 1980; Anderson et al., 1981; and Verma and Nelson, 1983; Harrison, 1984; Plue and Dobson, 1986). In order to minimize the total quantitative and qualitative losses during outside storage, the general recommendation is to keep the bales off the ground and to protect them from the rain.

In addition to straw, cereal grains also produce large quantities of

chaff (the chaff to grain ratio for wheat and barley is 0.24 and 0.11, respectively). For example, it has been estimated that over 4 million oven-dried tonnes of wheat chaff alone are produced annually in the prairie region. In 1985, Canadian Resourcecon (1983) Ltd. presented the results of a feasibility study of using chaff as the primary feedstock for a concentric vortex furnace for grain drying and space heating. It was concluded that the crop drying application had sufficient commercial potential to justify a recommendation to proceed with the fabrication and field testing of a chaff-fired furnace. However, no further work was done.

4.3.5 STOVER

Corn stover is the refuse left behind in the field after the harvest of the grain. It consists of stalks (35% of total dry weight), leaves (25%), husks (20%) and cobs (20%), and contains between 45 and 50% of the dry weight of a mature corn plant (Tyner et al., 1979). Ayres (1973) developed an equation to relate the dry matter yield of the various parts of the corn plant to grain moisture content. Corn stover left on the ground is a valuable deterent to soil erosion and a minimum of 2.2 t/ha should be left on the surface for erosive soils (Larson et al., 1978). With an average yield of stover of 6.28 t/ha, the amount that can be removed is about 4 t/ha. When plowed back into the soil, stover improves the organic content and soil structure and also provides some nutrients. Agronomists have estimated that the nutrient value of stover can be provided by fertilizer at a 1980 cost of less than $24.70/ha (Tyner et al., 1979). The main problem with utilizing stover as an energy source is that the moisture content at harvest is normally between 50 and 55% but may be as high as 70% in Ontario. Under proper conditions stover may be field dried from 50 to 30% in about 2

days; however, these conditions are frequently not present during the fall.

The ideal harvest package should be dense enough to shed rain when stored outside and still allow further drying. The two large packages for stover are the large round bales, formed by rolling, and the loaf-shaped stack, formed by packing coarsely shredded stover into a forage wagon. Richey et al. (1982) did time and cost studies on corn stover collection using a big roll baler and a large stack wagon. They found that about 30% of the available stover was recovered. Also, big roll bales at 33% m.c. and 128 kg/m^3 dry heated to 40 and 60 °C within one week after baling but cooled to near ambient temperatures within one month. Stacks at 30% m.c. and 44 kg/m^3 dry heated only to 20 °C and cooled rapidly, as did big roll bales at 14% m.c. and 103 kg/m^3. They also determined that the dry matter loss during outside storage to the end of May ranged from 10% for stover baled at 13.9% m.c. to 22.6% for stover baled at 33.4% m.c.

The costs of collecting corn stover in stack, big roll bales, and rectangular bales were compared by Claar et al. (1981). Maurya et al. (1981) simulated the energy input-output ratios for the harvesting, baling and transportation of corn stalks. They considered both large round bales and large stack wagon systems.

4.3.6 CORN COBS

Corn cobs are the densest fraction of corn residues and have been used as an industrial feedstock for over 100 products (Foley, 1978), including absorbents for degreasing, pesticides, blast cleaning of machinery, and cardboard box production. These uses were the result of the availability of large quantities of cobs when corn was harvested with the corn picker prior to the mid-1950's. However, cobs can also be used as a fuel for crop drying.

For on-farm use as a fuel corn cobs should be collected during the normal harvest (Smith et al., 1982). At typical harvest moisture contents of 30 to 50% (w.b.) cobs are not only difficult to store but their heat content is not optimal for burning. Dunning et al. (1948) studied the outside storage of corn cobs in large piles over a period of several years. They found that cobs with an initial moisture content of 12 to 18% showed moisture levels of 40 to 80% in the outer 0.9 m layer, while cobs inside the pile had about 33% moisture. More recently, Smith et al. (1985) published the results of a study of farm (3 to 18 t) and commercial scale (1000 to 2000 t) outside storage piles of corn cobs. Physical and chemical changes were measured during storage of up to eighteen months. Losses of up to 33% of the energy available in small piles were due to dry matter losses and increased moisture content during storage. Energy losses were reduced to 20% by drying the interior of some piles with ambient air. The authors concluded that outside storage of cobs in small piles is not practical in the Mid-West without losing a large proportion of the available energy. Furthermore, there is a health risk associated with handling of moldy cobs. It would therefore appear to be necessary to dry the cobs for use as a fuel in the same season as they are harvested.

In order to determine the drying characteristics of cobs, White et al. (1985) obtained the equilibrium moisture content data for broken cobs for both desorption and adsorption conditions at three temperature levels (10, 30 and 50 °C) and five moisture levels (5.7 to 27.5%). Cooper and Sumner (1985) determined the resistance of airflow through cobs and other biomaterials to allow fan selection for biomass drying and burning systems.

Sahm et al. (1981) developed simulation programs to estimate the economic effect of integrating cob gasification into existing farming systems

for grain drying. Cob collection in the combine grain tank or in a trailer was considered as part of the economic and energy cost analysis.

Haynes and Kline (1982) presented the results of three methods of harvesting, collecting and transporting corn residue during four seasons. The most promising approach used a combine mounted residue saver which delivered the residue to a forage wagon pulled behind the combine. The stover residue and the cobs were burned without further processing in a pilot-scale solid fuel furnace for drying shelled corn.

Bargiel et al. (1982) and Smith et al. (1982) have described systems involving modifications of the combine to move cobs along the straw walkers, pneumatic separation of cobs and husk material, a straw chopper mounted at the discharge of the combine and a forage blower to deliver the cobs to a trailing forage wagon. About 80% of the available cobs were collected while slowing the harvest rate by only 5%. Quaye and Schertz (1983) considered the design of a device to separate corn cobs from the combine discharge simultaneously with the corn harvest. The unit was based on counter rotating rollers for separating cobs from husks. Field tests indicated a high percentage of clean cobs and a high percentage of cob recovery. Schertz et al. (1984) and Morey et al. (1984) presented a system to collect cobs in the grain tank of the combine. The mixture of corn cobs and grain was separated automatically and continuously at the dryer site. The cobs were dried separatedly before being used as fuel.

Although most of the work on corn cob use has been done in the United States, some work has been done elsewhere. Thus, Gautier (1982, 1985) reviewed the use of cobs and straw as fuels for grain drying in France. Combines with rotary cleaners were observed to harvest 80% of the cobs

without impairing the grain quality. Kocsis (1982) presented a summary of the work on biomass collection and use in Hungary. He concluded that the cost of the systems was still too high compared with other fuels. An interesting aspect of the review was that it mentioned the use of geothermal energy in agriculture.

Milande (1981) presented design details of a cob-fried biomass furnace used to dry grain corn in the U.K. The paper stressed the technical feasibility of the system.

4.3.7 BURNERS AND GASIFIERS

Residue burners for drying grain are either direct-fired, usually employing gasification, or indirect-fired using a heat exchanger. In recent years there has been greater emphasis on the development of direct-fired residue furnaces to dry grain by gasification and combustion.

In addition to the simple single chamber furnaces, two-stage gasifiers and concentric vortex furnaces have been designed and evaluated. Single chamber furnaces are basically the same as wood stoves in design; although some modifications have been made to capture the heat. For example, the chamber may be enclosed by a shell in which the combustion air or the drying air is preheated. In some instances, water used for space heating systems is heated in the shell.

In the two-stage gasifiers the biomass is burned at low temperatures to produce volatile gases which are burned in the second stage. The flow of the gases may be upward or downward; hence the terms updraft and downdraft gasifiers. The gasifiers are more efficient than single chamber burners but are also more difficult to operate. Two of the main problems are the development of hot spots with corresponding slag formation and particulate

emissions. The concentric vortex furnace is based on the formation of spiral gas flows and resembles a cyclone. The combustion air and fuel enter the furnace tangentially from the side or top causing them to mix thoroughly. Combustion takes place at the centre of the chamber in a spiral flame. The hot combustion gases leave the chamber through the top, while the ash settles to the bottom as in a cyclone. The concentric vortex furnace is also more efficient than the single chamber units.

All furnaces form part of a systems, which includes feeding of the fuel. Much of the research has been done using manual feeding systems; however, for practical use in grain drying it is desirable to have automatic feeding so that the system can be left unattended for several hours.

a) Straw burners and gasifiers.

Most of the R&D work on straw-fired furnaces and gasifiers has been done in Europe. Wilton (1975) reported that a straw burning furnace and crop dryer were added to the chop treshing system at Nottingham University in the U.K. The total process involved windrowing and conditioning the cereal crop in the field before it was collected with a forage harvestor and taken to a rotary drum dryer. After the crop was dried, the grain was separated and the straw fed into the furnace. He found that there was enough energy in the straw to dry the entire crop.

Recently, Metcalfe (1986) presented the results of 10 case studies of straw or wood fired furnaces for agricultural and horticultural applications in Great Britain. Only one of the cases involved drying of grain while another one dealt with drying of onions. The grain drying system used a biomass furnace to heat water and a heat exchanger to heat the drying air. The remainder of the cases covered heating of greenhouses, livestock

buildings, farm houses and water. All of the furnaces were commercial units, mostly manufactered by Passat Heating Ltd. Some systems were large enough to accept up to 12 rectangular bales or two large cylindrical bales. Furnace reliability was found to be good but refuelling was the limiting factor for unattended operation. The majority of efficiencies were in the range of 40 to 60% but in several cases the efficiency was found to vary significantly as the fuel charge burned down. Automatic fired units showed average combustion efficiencies of 71 to 73%.

Blake (1982) compared the costs of oil- and straw-fried systems in the U.K. and concluded that the additional capital cost resulted in a substantial annual loss for the iomass system even though there was a 59% savings in fuel cost. Mwaura et al. (1982) came to similar conclussions for U.S. - built biomass furnace drying systems under 1983 U.S. economic conditions.

One of the first German designs consisted of a vertical cylindrical combustion chamber, which held 3 to 5 square bales of straw. Charging was done manually through the fire door at the front of the furnace. Approximately 20,000 of these furnaces were in use in 1980, although most of them were used for burning wood wastes rather than straw. Performance tests have shown that the particulate emission rate was above the allowable maximum of 300 mg/m^3 of combustion gases. The original design has been changed to include a secondary combustion chamber and other modifications to ensure high operating temperatures and lower emission rates (Strehler, 1979, 1981, 1983).

Various other designs involving controlled primary and secondary combustion have been marketed. One example of a high efficiency furnace is the German PSW Waste Combustion Plant. Bales of straw, chopped crop residue,

sawdust or bark are partially combusted to low-temperature carbonized gases which are then completely burned in the after-burning channel by injecting fresh air. The hot gas flow of about 1200 °C is passed through heat exchangers for water or air heating. The company producing these units claimed emission rates of less than 300 mg/m^3 and an efficiency of 80%. Peill (1980,1981) tested a PSW big-bale straw-burner, model VBA-GBO-HT, at Lyndhurst Farms Ltd., Canning, Nova Scotia, under contract to Agriculture Canada. The furnace was used to dry about 1200 t of wheat and 800 t of corn in a MC-600 continuous crossflow grain dryer using straw as the only fuel. The unit was also used to heat a 250 sow farrow-to-finish operation. The total energy demand for drying and space heating required about 360 to 450 t of straw per year. The straw was harvested from only 120 to 140 ha, leaving a 0.30 to 0.45 m stubble in the field.

Peill (1984a) worked on the development of a practical, economical way to dissolve big bales of straw (1.8 m dia x 1.8 m long) into chopped straw for continuous feeding of the PSW burner. During the 1982 and 1983 grain drying seasons about 178 t of straw was used to dry the cereal grain crop and the corn crop. It was observed that the amount of flyash was substantially reduced by the use chopped straw rather than complete bales. It was also possible to maintain a constant combustion rate, while the ash was in the form of a crushed powder instead of slag. The straw consumption for the two years was 40.6 kg/kg of water removed. Although there were savings of $44.40/h of drying with straw instead of propane, Peill concluded that at least 1900 h of operation were necessary to offset the capital cost. In fact, after working for five years with the complete large bale harvesting and combustion system, he concluded that the returns did not

justify the cost.

The PSW burner was also examined by Vander Kloet (1983) under contract to the Nova Scotia Department of Mines and Energy but the results of the work were unavailable.

Based on the experience with the PSW burner, Peill (1984b) developed a small bale gasifier for a water heating system. The maximum output from the unit was 160 MJ/h at an efficiency of about 70%. Two to three small bales of straw were fed into the primary combustion chamber every hour. After 200 days or 2000 hours of operation the stainless steel part of the second stage afterburner had completely deteriorated and had to be replaced. Also, it was estimated that the refractory bottom in the second stage would last about five years. When a market value of straw of $70/t was used, the cost of operating the gasifier was $3463 as compared with $2217 for an equivalent oil furnace.

In the late seventies the Stormor Company developed a crop residue furnace for their Stormor Ezee Dry batch-in-bin dryer. With a 3m x 3m x 3m combustion chamber the furnace could be fed with either large round bales or large stacks. The drying air was heated by passing between the walls of the combustion chamber and outer furnace shell so that no combustion gases and particulates would enter the grain. Moorehouse (1979), who is a Stormor distributor in Ontario, used one of the unit to dry corn with large round bales of straw. He found that the need to open the large doors to add bales while the furnace was in operation was a problem. In a number of instances the new bale would start to burn before it was properly deposited in the furnace. He also found ash accumulation to be a significant problem in operating the furnace on a continuous basis. The operating efficiency of the unit was only about 30%. Moorehouse (1987) has made various modifications

and design changes over the years and most of the earlier problems have been solved.

b) Corn residue burners and gasifiers.

Horsfield (1976) presented a summary of his observations during visits to England, France and Sweden in 1976 to review research on gasification. Although some of the current work was described, none of it dealt with crop drying. However, it appears that information obtained during the visits led to the development of an experimental corn cob burner (Horsfield et al., 1976). Further work with the unit led to the design and construction of two pilot plant demonstration systems (Williams et al., 1978). One unit supplied 10 GJ/h as hot, particulate-free gas to the burner in a steam boiler. The second unit generated fuel gas from corn cobs which is cleaned, cooled and supplied to a 135 kW dual-fuel, turbo-charged, intercooled diesel engine that is direct-coupled to a 75 kW generator. Both units were placed on trailers for on site demonstrations. Although the systems were not used for grain drying, the gasification technology and equipment could be used for that purpose.

Sumner et al. (1983) evaluated the performance of a Stormor biomass grain drying system, which consisted of a batch-in-bin dryer and an indirect-fired furnace. They found that large round bales of cotton stalks, corn stover and soybean residue burned satisfactorily in the 28 m^3 firebox. The heat extracted from the heat exchanger was determined to be 49 to 69% of the biomass energy input to the furnace.

Sukup et al. (1982) reported the performance results of a biomass furnace developed by the Sukup Manufacturing Company. To burn a mixture of cobs and husks (husklage) it was necessary to use at least 50% excess air to

ensure complete combustion. The maximum output of the burner was 3200 MJ/h. The Sukup system was also tested by Huffman and L'Ecuyer (1985) under contract to Agriculture Canada.

Kajewski et al. (1977) used a direct-fired residue burner to dry grain corn. Shredded corn stalks were fed into the furnace at a rate of 180 kg/h resulting in exhaust temperatures of 380 to 400 °C. After mixing the exhaust with ambient air the drying air entering the batch-in-bin dryer was 70 to 90 °C. It was determined that about 8% of the stalks produced were required to dry corn from 25 to 15% m.c. Payne and Ross (1979) also designed a farm size gasifier combustion system for a direct-fired unit to convert crop residue into thermal energy for grain drying. Claar et al. (1980) discussed the application of a 2.64 GJ/h direct-fired, concentric-vortex furnace that burned agricultural residue in a wide variety of forms to dry grain in a 4.14 t/h continuous-flow grain dryer. Additional results were presented by Anderson et al. (1981) and Wahby et al. (1981). Kranzler and Stone (1982) also worked with a concentric-vortex biomass furnace. Their prototype unit included a ram bale feeder to obtain continuous furnace performance. They reported that a clear, radiant stack was maintained over a 2:1 turndown ratio and excess air range of 50 to 250%. The average conversion efficiency was 64% and the maximum heat release was 0.4 MJ/h.

Payne et al. (1979) reviewed the design criteria for a gasification-combustion process in order to build a 200 kW experimental burner for burning corn cobs, fodder and grain. Similarly, Mwaura et al. (1983) built and integrated a concentric vortex-cell biomass furnace into an in-bin counterflow dryer (Shivvers System). The average energy consumption was 9 MJ/kg of water removed when drying corn from 26 to 15.5% (w.b.) with

woodchips, corn cobs or shelled corn as fuels. The average biomass consumption was 50 kg of dry matter per metric ton of corn. No visible colour or odour changes, or soot deposits were detected on the grain.

Richey et al. (1982) developed a prototype biomass furnace with a gasification primary stage and a gas combustion secondary stage. Initial tests were conducted with cobs as the fuel and with the exhaust used for direct drying of grain corn. Four batches of corn of about 21 m^3 each were dried from 21.5 to 15% m.c. at a specific energy consumption of 6.3 MJ/kg of water removed. It was concluded that about one-third of the cobs were sufficient to dry the grain. Subsequent modifications to the furnace to allow for downdraft action resulted in a hotter and cleaner exhaust (Richey et al., 1981). Various other design modifications were made during 1982 and 1983. A review of these units and their performance was described by Richey et al. (1985). An automatic corn cob feeding system for the gasifiers was presented by Richey and Barrett (1983).

Foster et al. (1982) used a corn cob gasifier with a combination drying system. The gasifier supplied heat for the high-temperature drying phase, while solar energy was used for the low-temperature phase. They concluded that there was enough savings in using cobs at $22.00/t to justify further work on the system.

Morey et al. (1984) used a downdraft furnace with a 400 to 800 kW heat output to dry corn with a continuous flow dryer (Lindsay Model 600D). Although the exhaust products were put directly into the drying air, the corn's appearance or odour were not affected.

Spieser (1986) presented the operating data of a corn cob fueled boiler which had been developed by McKinlay Energy System Inc. to provide hot water heating for two chicken broiler barns, machine shed and home. The unit

recovered about 53% of the thermal energy contained in the cobs for an energy output of about 300 MJ/h. After assuming that dry cobs could be purchased at a cost of $15/t, it was calculated that the total system had a payback period of 6 to 7 years. The operating savings were 72% compared with a natural gas furnace of the same output.

McKinlay Energy System Inc. has reached an agreemnet with Newmc Mfg. Inc. of Woodstock, Ont. to develop a prototype burner/barter unit which will meet the high-performance standards of the commercial market. Newmac Mfg. Inc. demonstrated a 300 MJ/h unit at the 1986 International Plowing Match. Further changes have been made and the company expects to market a commercial boiler for space heating in 1988 after completing an extensive test program in the fall of 1978 and winter of 1988, (Newport, 1987). No plans have been made to produce a burner of sufficient capacity to dry grain.

In addition to those mentioned above, a number of other crop residue furances have been developed and evaluated in Canada for both space heating and drop drying. A summary of those is found in Table 4.3.5. Except for those referenced earlier, little information was found on those systems.

4.3.8 EMISSIONS

From a cost and efficiency point of view it would be desirable to use the exhaust gases directly to heat the drying air; however, the exhaust gases contain particulates and trace chemicals which, if absorbed or deposited on the grain in sufficient quantities, could result in contaminated grain. Trace chemicals considered to be of concern in this context are nitrogen oxides, sulfur oxides, and poylnuclear hydrocarbons. While the sulfur and nitrogen oxides may result in corrosion problems with

the equipment, nitrogen oxides may also react with exposed protein to produce carcinogenic nitrosamines. Similarly, the main problem with particulates is the possible presence of polynuclear hydrocarbons, such as benzo(a)pyrene (BaP) which is a known carcinogenic agent. The level of BaP is an indicator of the level of carcinogenic factors in the exhaust of combustion processes (Boubel and Ripperton, 1963), while the amount of total gaseous hydrocarbons (THC) is a measure of the completeness of combustion. Although the amount of contaminants in the exhaust is important, the deposition of contaminants will determine the quality of the dried grain. Total particulate and particulate absorbed B(a)P emissions may be measured using EPA Method 5 techniques and procedures. These have been outlined and discussed by Jacko and Barrett (1981) and Desilets et al. (1984). For comparison purposes; it may be useful to use the fact that the acceptable B(a)P content in several European countries for various smoked food products is 1 ppb (ug/kg)* (Hutt et al., 1978).

Anderson et al. (1981) obtained corn dried in a continuous flow dryer heated with a cob-fueled furnace and attempted to determine the harmful deposits using a biological test of carcinogenic potency (Ames test). However, the corn sample was too small to provide conclusive results. In subsequent experiments Anderson et al. (1983) found the B(a)P levels on corn dried with cobs and a cob-husk mixture to be less than 2 ppb which was said to be lower than such foods as charcoal broiled steak (50 ppb) and cereal grains used for human consumption (0.1 to 60 ppb). The particulate levels on the corn varied from 2.3 to 126.8 mg/MJ.

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* ug = microgram

Payne et al. (1983) performed an analysis of the exhaust from the gasification-combustion of corn cobs under laboratory conditions. The particulate emission rate was proportional to the second power of the gasification rate and the deposition potential was calculated to be 0.1 gm of particulate per kg of grain dried. The BaP emission was equivalent to that from gas or oil fired burners of the same size and was found to increase with increasing emission of unburned char. The emission rate could result in a deposition of 0.136 g/kg of corn dried. The THC emission was less than 30 ppm which indicates that the combustion process was almost complete.

Mwaura et al. (1983) dried corn in an in-bin counterflow dryer heated with a concentric-vortex cell biomass furnace fueled with woodchips and corn cobs. They analyzed the corn for poly-cyclic aromatic hydrocarbons (PAH) and heavy metal contamination. The PAH concentration of 0.06 to 8.6 ppb was of the same order of magnitude as that found in corn dried with direct heated fossil fuel dryers (Hutt et al., 1978), while the concentration of heavy metals was negligible.

In 1981, Barrett et al (1983) determined the mass emission rates and aerodynamic size distribution of particles emitted from three biomass burners; namely, a direct combustion cob and stalk burner made by Sukup Mfg. Co. (Sukup et al, 1982), an updraft gasifier corn cob furnace built by Clayton and Lambert Mfg. Co., and a downdraft furnace developed by Purdue University and USDA. The particulate mass emission rates of all three units were substantially higher than from a liquid petroleum burner and the average emission rate of 158 mg/MJ was also greater than the level of 43 mg/MJ allowed by the EPA's New Source Performance Standards for large coal fired boilers. Ninety percent, by weight, of the flyash particles were less than one micron in aerodynamic diameter. Their mass mean diameter was about

0.2 micron. About 50% of the flyash was deposited in the first metre of the grain bed. In a concurrent study Jacko et al. (1982) identified eight PAH compounds in the combustion air but found their deposition on corn was negligible and of the same order of magnitude as found on freshly harvested corn.

Particulate emission tests from three multi-channel downdraft gasifier furnaces developed at Purdue showed emissions 22 times greater than the average emissions of natural gas and propane. Cob moisture content in the range of 9 to 26% did not affect the particulate emission rate to a significant degree. BaP emissions averaged 0.031 and 3.0 ug/MJ input for the Purdue '82 and Purdue Pilot gasifiers, respectively. Emissions from the Purdue '82 unit were about one-half that of a gas-fired space heater, and twice that of propane burners used to dry grain. NO_x concentrations were found to increase with higher gasification rates and were about three times greater than reported for natural gas or oil burners used for space heating (Barrett et al., 1984; Richey et al., 1985). Thimsen and Morey (1981) also analyzed the exhaust from a two-stage downdraft biomass laboratory furnace developed by them.

In order to reduce the emissions from biomass furnaces, some investigators have considered gas scrubbers as part of the system (Pedersen, 1981; Nielsen and Berthelsen, 1982; Nielsen, 1982; LePori and Parnell, 1983). The addition of emission abatement equipment increases the cost of the system and makes the use of biomass too expensive for such short term applications as grain drying. On the other hand, if the burner could also be used for space heating, the additional expense may be acceptable.

The response of animals to corn dried with the exhaust from a biomass

furnace was studied by McNeill et al. (1984). During 1982 and 1983 swine and poultry were fed corn dried with wet or dry cobs and corn dried with a propane system. It was concluded that the drying system did not have a major impact on the feed intake and the growing rate. Therefore, any particulate that may have been deposited on the corn did not affect the gain of the animals.

4.3.9 SUMMARY

1. Some thermophysical properties of crop residues and other biomass resources have been determined and are available; however, a more complete data base would aid the design of equipment and systems.

2. The amount of thermal energy in crop residues is sufficient to dry grain. In general about 20 % of the cobs or stalks is sufficient to dry the grain.

3. Harvesting, collection and handling of residues has been studied using systems models. Some equipment has been designed and tested; however, more work is needed to optimize these operations and to determine the long term effects of residue removal on the soil.

4. Storage of straw, stover, cobs has received considerable attention. In most instances it is necessary to protect the material from the weather during the storage period. Polyethylene sheets placed over the bales have provided sufficient protection to prevent spoilage and rain penetration.

5. Straw can usually be field dried to a suitable storage moisture but stover and cobs may need artificial drying before being used or stored. Further work may be needed to determine field drying and artificial drying criteria for specific locations.

6. Straw burners and gasifiers have been developed and are commercially available; however, additional work appears to be needed to facilitate automatic loading of large round bales.

7. Sufficient data are available to design a commercial corn residue gasifier; however, the selection of an optimum design may prove to be somewhat more difficult.

8. Considerable research has been done to quantify the emissions from residue gasifiers and burners. The amount of particulates was in almost all cases too high to meet environmental standards and the use of pollution abatement equipment may be necessary.

9. The combustion products absorbed on the grain have been identified and quantified. It would appear that in most instances the amount of absorbed material is not high enough to cause concern. Nevertheless, additional efforts are needed to verify this conclusion, especially as far as B(a)P and other carcinogenic materials are concerned.

10. Some researchers have concluded that the use of crop residue for crop drying is competitive with conventional fuels at current prices; however, others showed that the significant savings in energy costs (up to 50%) are more than eliminated by the high capital cost of biomass-fried systems. Multiple use of the systems would imporve the economic feasibility.

11. Use of crop residues is also less convenient than use of conventional fuels, additional equipment and labour at a time when most farmers are very busy with the harvest.

12. Little information has been published on the long term maintenance and operation of gasifiers for crop drying systems.

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FIGURE 4.3.1 SUMMARY OF BIOMASS CONVERSION PROCESSES (Otten, 1981)

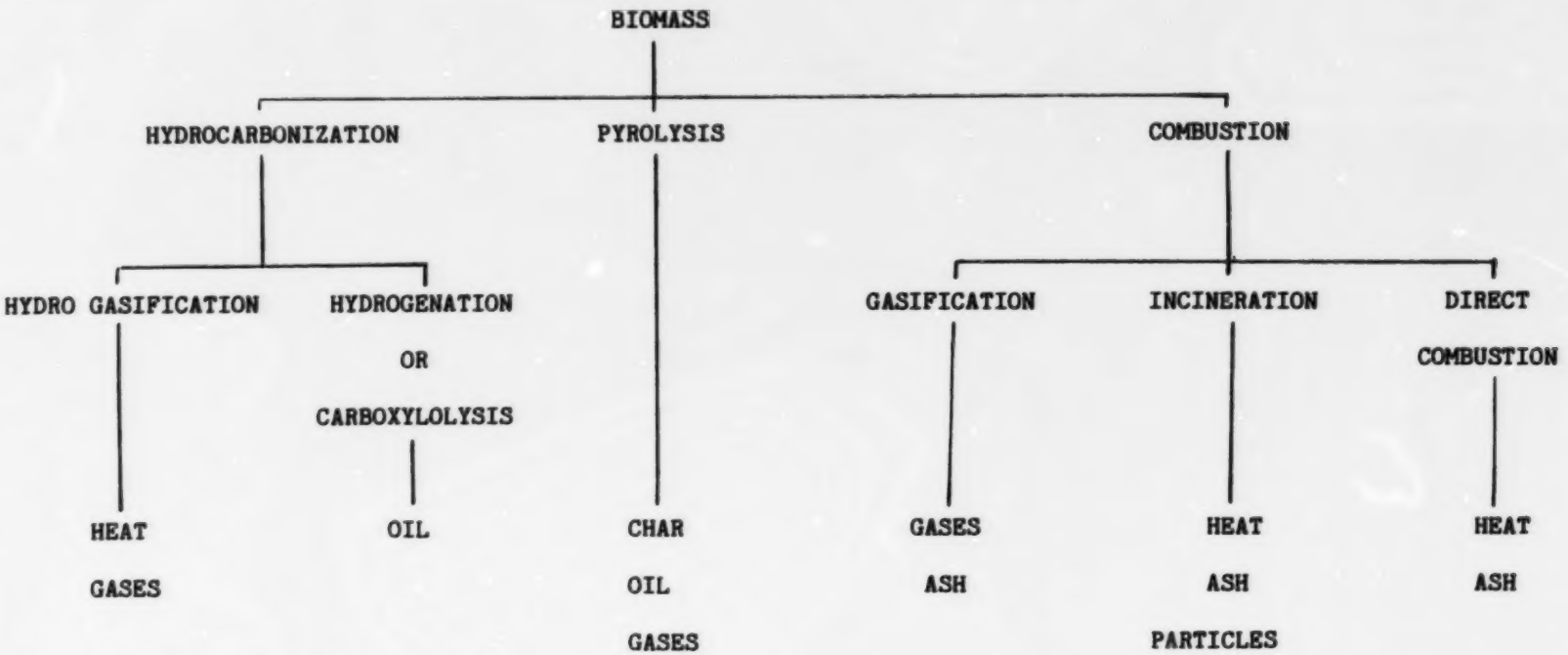

TABLE 4.3.1 AVERAGE WHEAT/OATS/BARLEY STRAW AND STOVER PRODUCTION, 1973-75, (INTERGROUP CONSULTING ECONOMISTS LTD. 1978)

Region	Straw and Stover (000 tonne)	County	Straw and Stover (000 tonne)
Southern	2610	Elgin	287
Western	980	Essex	241
Central	380	Kent	628
Eastern	217	Middlesex	387
Northern	44	Oxford	295

TABLE 4.3.2. HEATING VALUES AND ANALYSES OF CROP RESIDUES (Ebeling and Jenkins, 1985).

	HHV (MJ/kg)	LHV (MJ/kg)	PROXIMATE (% by weight d.b.) VOM	ASH	FC	ULTIMATE (% by weight d.b.) C	H	O	N	S	Cl	Residue
WHEAT STRAW	17.5	16.49	71.30	8.90	19.80	43.20	5.00	39.40	0.60	0.11	0.28	11.40
BARLEY STRAW	17.31	16.24	68.80	10.30	20.90	39.92	5.27	43.81	1.25			9.75
CORN COBS	18.77	17.58	80.10	1.36	18.54	46.58	5.87	45.46	0.47	0.01	0.21	1.40
CORN STOVER	17.65	16.52	75.17	5.58	19.25	43.65	5.56	43.31	0.61	0.01	0.60	6.26
CORN STALKS	15.83	14.79	65.40	17.30	17.30	39.47	5.07	39.14	1.20	0.02		15.10

TABLE 4.3.3 CALORIFIC VALUE OF STRAW. (STREHLER, 1979)

MOISTURE CONTENT %	10	12	14	16	18	20	25	30
CALORIFIC VALUE, MJ/KG	15.1	14.7	14.3	13.7	13.5	13.1	12.1	11.0

TABLE 4.3.4 COMPARISONS OF SEVERAL FORMS OF STRAW PACKING (STREHLER, 1979)

	CHOPPED STRAW	BIG BALES	PELLETS	SQUARE BALES
SPECIFIC WEIGHT kg/m^3	50	100	300-500	80-100
WEIGHT PER UNIT kg	-	300-400	0.02-0.2	10
STORAGE ROOM m^3/60000 kWh	370	245	41	200
PRODUCTION COSTS	++	+	—	0
APTITUDE FOR TRANSPORTING SHORT WAYS	-	++	++	0
APTITUDE FOR TRANSPORTING LONG WAYS	—	0	++	+
FEEDING OF FURNACE	CONTINUOUS	INTERMITTENTLY	CONTINUOUS AND INTERMITTENTLY	INTERMITTENTLY
POSSIBILITY OF AUTOMATIZATION OF FEEDING	-	—	++	+
POSSIBILITY OF AUTOMATIZATION OF FEEDING	++	-	++	-
POSSIBILITY OF REGULATING CAPACITY	++	-	++	-
COMBUSTION SYSTEM	DUST BURNER, FURNACE FOR SOLID FUELS WITH AUTOMATIC FEEDING	SPECIAL STRAW FURNANCES WITH SECONDARY COMBUSTION		

Notice: ++ = very suitable; + = suitable; 0 = neutral; - = less suitable
— = not suitable or impossible

TABLE 4.3.5 RESIDUE BURNING PROJECTS (SOURCE: CANADIAN RESOURCES (1983) LTD., 1985)

NAME	LOCATION	RESIDUE	APPLICATION
W. Keith	Sovereign, Sask.	Flax Straw (square-bale)	House and Shop Heating
R. Naurocki	Beausejour, Manitoba	Wheat Straw (round-bale)	Corn Drying
Genstar	Winnipeg, Manitoba	Flax Straw	Process Heat
J. McKinny (NUMAC Mfg. Co.)	Thamesville, Ontario	Corn Cob	5 HP Boiler for Heating
R. Hunter	Whitby, Ontario	Soya Bean Straw and Wood Waste	Crop Drying (10GJ/h)
R. Moorehouse	Florence Ontario	Corn Cob and Round-bale Straw	Crop Drying
J. Vonk	Bradford Ontario	Flax Straw (chopped) and Sae Dust	30 HP Boiler for Greenhouse Heating
J. Smith	Port Ryeserse Ontario	Variety of Crop Residues	Boiler Design for Grain Drying
J. Peill	Canning, Nova Scotia	Chopped Straw (square-and) square-bale)	Grain Drying (ATAHE)
G. Visser	Orwell Cove, P.E.I.	Straw (square-and) Wood Waste	Grain drying (ATAHE)
A. Witting	Meadow Bank, P.E.I.	Straw	Grain Drying

5.0 GRAIN CHARACTERISTICS

5.1 INTRODUCTION

All of the previous systems have dealt with drying processes and equipment without considering the physiology of the grain to be dried. Some of the equipment and process changes have resulted in significant improvements in energy use and grain quality. In contrast to the activity in those areas, little attention has been paid to improve the drying characteristics of the grain through a change in the physical and biological properties, either through breeding or mechanical processing before drying.

The following review will address some of the work done to determine the effect of various physiological factors on the drying rate of grain corn. It will also present the results of experiments performed in Hungary in reducing the effect of one physiological property, the pericarp thickness.

5.2 PHYSIOLOGICAL FACTORS RELATED TO THE DRYING RATE OF CORN

Many studies on field drying of corn have shown large differences in the drying rate among corn strains after physiological maturity. Corn has reached physiological maturity when the kernels have reached the maximum dry weight (Purdy and Crane, 1967a). Higher field drying rates result in lower moisture content at harvest and reduce the cost of artificial drying.

5.2.1 EFFECT OF PLANT COMPONENTS ON FIELD DRYING

a) Effect of leaf area and husk

The contribution of various parts of the plant to the field drying rate of an ear of corn after physiological maturity has been studied by Troyer and Ambrose (1971). They found that the drying rate of an ear was not associated with the leaf area of the plant which affects the rate of

evapotranspiration. Instead the characteristics of the husk and the amount of moisture received from the plant through the shank controlled the ear moisture content. Thus, higher drying rates were associated with shorter husk and lower husk number. The effects of the cob and kernel characteristics were not considered in their research.

b) Effect of ear components

Crane et al. (1959) studied the drying behavior of husked ears, shelled kernels and cobs as potential factors contributing to field drying differences between corn strains. Husked ears, kernels and cobs from two hybrids were weighed at harvest and after 6, 16 and 28 of drying at 38°C in a forced-air dryer. The drying rate of the cob was the same for the two hybrids tested; however, a marked difference in drying rate of the ears and kernels between hybrids was found. This suggested that differences in artificial drying rates also exist between corn hybrids since a forced-air dryer was used for the experiment.

The osmotic diffusion pressure of kernels from a fast and a slow drying hybrid was also studies by Crane et al. (1959). Kernels were soaked for two hours in a graded sucrose solution. The kernels from the slow drying hybrid showed a slightly higher osmotic pressure which is another indication that kernels of different corn strains vary in their moisture diffusion properties.

c) Effect of ear size

The effect of ear size on the field drying rate differences of three slow-drying and three fast-drying inbreds was studied by Purdy and Crane (1967a). Husked ears from each inbred were dried in a forced-air dryer for 18 at 38°C to determine the drying rate. They found that heavier ears were

associated with slower drying rates, and suggested that larger ears have less exposed surface area per unit weight.

It is not clear from their study whether the effect of ear weight was fully explained by the surface to weight ratio since the surface was not measured, only the weight. It is possible that the density of the ears was different. If this were the case, the effect of ear weight on the drying rate could also be explained by higher ear density. Since the density was not measured it is not possible to separate this effect from the effect of exposed surface area. It is probable, therefore, that the artificial drying rate of shelled kernels could also be affected by the kernel density. It is well accepted that the exposed surface area of kernels affects the drying rate. It is not known however, whether the differences in surface-to-volume ratio and density of kernels are large enough between corn strains to create significant differences in drying rate.

d) Effect of kernel size and shape

The effect of size and shape of kernels on the drying rate of shelled corn was studied by Chu (1966). It was suggested that the change in moisture content of a solid at the initial stage of drying is confined to the neighbourhood of the surface. Based on this hypothesis it was deduced that the average moisture ratios at the beginning of drying for solids of different shape are the same if their surface-to-volume ratio are equal. The effect of shape was analyzed from a theoretical point of view by comparing the solution of the diffusion equation with a constant diffusion coefficient for a plane sheet, a cylinder, a sphere and a cube. It was found that for the same surface-to-volume ratio, the drying rates were almost identical for all shapes when the moisture ratio (MR) < 0.4.

A total of 433 thin-layer drying tests were performed on shelled corn by Chu (1966). The tests were divided into eight groups according to the drying conditions while the kernels were graded according to their width, thickness, and length. A numerical solution of the diffusion equation for a sphere with a moisture dependent diffusion coefficient was used by Chu to fit his experimental data. The kernels were considered to be equivalent if their surface-to-volume ratios were the same. The surface-to-volume ratio was obtained from he kernel dimensions (length, width and thickness) and by assuming that the kernel shape was a rectangular parallelepiped. The radius of a sphere with the same surface-to-volume ratio was used for the theoretical solution. It was found that the theoretical solutions fitted the experimental data well in the first ten hours of drying and the largest error for most runs was within 0.5% moisture content. Chu concluded that the effect of size and shape of kernels was well described by the idea of an equivalent surface-to-volume ratio.

5.2.2 EFFECT OF CORN KERNEL PHYSIOLOGY

A corn kernel may be divided into the hull, the endosperm and the germ. The weight proportions of each component on a dry basis are approximately 82% for the endosperm, 12% for the germ and 6% for the hull.

The hull consists of a series of cell layers covering the kernel. The pericarp is the outer layer and mainly consists of dead, elongated, thick walled cells forming a tough and dense tissue. The pericarp covers most of the kernel except at the base where it joins the tip cap. The tip cap is the remnant of the tissue connecting the kernel to the cob and is made of star-shaped cells which are well adapted for rapid moisture absorption (Inglett, 1970).

The endosperm is divided into the horny and floury endosperm. The proportion of horny and floury parts vary considerably according to the type of corn. For instance, the horny and floury parts for dent corn are in the ratio of about 2:1, whereas the popcorn and flint corn the endosperm is mainly horny with a small floury central core.

The germ is located under the hull at the side of the tapering end of the kernel and has a pyramidal shape. Although the germ accounts for only 10-12% of the dry kernel weight, it represents about 30% of its volume (Boumans, 1985). Under favourable germination conditions the moisture content of the germ is 60% while that of the endosperm is only 25%.

a) Effect of endosperm type

Hunter et al. (1979) studied the effect of endosperm type of the field drying rate of corn. No major differences in drying rate between hybrids with flint and dent endosperm were found.

The effect of endosperm mutants on drying of husked corn ears was studied by Nass and Crane (1970). The drying rate was defined as the reduction of moisture in percentage points from husked ears placed in a forced-air dryer for 24 hours at 38°C. A total of nine endosperm mutants with three hybrid background were used for the study. They found that the drying rate differed significantly between ensoperm types. They proposed that the amount and type of hydrophylic compounds such as sugars, proteins and carbohydrates present regulate the amount of water held and the rate of water released by the endosperm. In other words, the equilibrium moisture content and the diffusion coefficient are affected by the amount and type of hydrophylic compounds present in the endosperm. It appears, therefore, that the endosperm composition is also a factor contributing to drying differences

among hybrids.

Although the drying tests were performed with husked ears, it is likely that the endosperm mutant would also influence the drying behavior of shelled kernels. It is not clear, however, the extent to which the endosperm creates differences in the artificial drying rate of kernels.

b) Effect of pericarp

The influence of pericarp on the drying rate of different corn strains was studied by Purdy and Crane (1967b). The drying rates of slow and fast field drying hybrids were correlated with the permeability and the thickness of the pericarp. The drying rate was estimated by measuring the moisture loss from husked ears kept in a forced-air dryer for 18 hours at 38°C. The pericarp thickness was measured with a microscope at 125 X magnification from transverse sections of eight microns thick made with a freezing microtrome at -10°C. The permeability of the pericarp was obtained by measuring the rate of water diffusion from pure water to a 1.5 M sucrose solution through an excised pericarp disk of 215 mm^2. It was found that the drying rate was highly correlated with pericarp thickness and permeability. A higher drying rate was associated with more permeable and thinner pericarp. Unpublished data obtained at Guelph support this observation (Ho et al., 1975). Since pericarp characteristics influence the drying of husked ears, it is likely to influence the kernel drying rate as well.

For the pericarp to have an effect on the drying rate of kernels its diffusivity must be lower than that of the other components because the pericarp consists of the first 10 or so layers of cells surrounding the kernel. In other words, the resistances to moisture diffusion of the pericarp and the rest of the kernel, consisting of the germ and endosperm,

are in series. The component with the lowest moisture diffusivity has the greatest influence on the drying rate of the kernel.

The moisture diffusivity of the various components of corn and soybeans has been reported in the literature. Mensah et al. (1979) measured the diffusivity of soybean seedcoat (pericarp) and cotyledons. The seedcoat was removed from the cotyledons and both components were dried in a thin-layer dryer. The moisture diffusivity was obtained from the actual drying data by considering the seedcoat and the cotyledon to be flat plates. The cotyledons were cut to obtain flat plates of 8 mm long, 7 mm wide and 1 mm thick before drying. The seedcoats were approximately 0.1 mm thick, 5 mm wide and 9 mm long and did not need to be cut as they already have the shape of a flat plate. Drying experiments were done at three temperatures (35°C, 45°C, 55°C) and three relative humidities (25%, 45%, 70%) for a total of nine different drying conditions. It was found that moisture diffused approximately six times faster through the cotyledons than through the seedcoats.

Moisture diffusion through various components of a corn kernel was measured directly by Syarief et al. (1984) using a method developed for the purpose. Moisture diffusion through a 4.6 mm diameter spherical molecular sieve (4°A) was measured to validate the procedure. It was found that the average difference between the diffusion coefficient of the molecular sieve determined with the new method and the known value was 20 percent. Consequently, the method for the measurement of moisture diffusion coefficient of the corn was considered suitable. The moisture diffusion coefficients were plotted versus the moisture content of various kernel components. The diffusion coefficient of the pericarp was much lower than that of the

other components, which is consistent with the findings of Mensah et al. (1979) for soybeans.

The permeability of the seedcoat (pericarp) to various mercury compounds for three dent and four sweet corn varieties was studied by Orton (1927). It was found that the permeability to each mercury compound varied with the corn variety. The permeability of pericarp to water by osmotic pressure has also been found to be different amount corn strains by Purdy et al. (1967b). This is an indication that the rate of moisture diffusion through the pericarp differs among corn hybrids.

Since the pericarp has been shown to have a significantly lower permeability than the other components, it is likely to influence the kernel drying rate. Therefore, differences in the thickness and permeability of the pericarp among corn strains could results in kernel drying rate differences.

Numerous investigations have been done to measure and compare the pericarp thickness of various corn inbreds/hybrids. Most workers have found large differences (Richardson, 1960; Wolf et al., 1969; Helm and Zuber, 1969, 1970; and Ho et al., 1975). Helm and Zuber (1969) measured the pericarp thickness of mature kernels of 33 inbred lines for four years. Six measurements were made at the same location with a plunger micrometer on each of the 50 pericarp samples per inbred. The average pericarp thickness for the four years of measurement ranged from 0.62 to 0.160 mm. Ho et al. (1975) used the same method to obtained the pericarp thickness of 16 inbred lines for one year. Their results showed the pericarp thickness to range from 0.035 to 0.126 mm.

The hygroscopic properties of soybean seedcoat and cotyledons was studied by Mensah et al. (1979). The equilibrium moisture content (EMC) was measured at various temperatures and relative humidities. The seedcoat and

the cotyledon was separated and then equilibrated over saturated salt solutions to obtain the EMC. The heat of desorption of each components was obtained empirically for various moisture contents using the Clausius-Clapeyron equation. The heat of desorption is an indication of the binding energy or the intermolecular forces between the water vapor molecules and the surface of the absorbent. It was found that the EMC and the heat of desorption of the seedcoat was higher than those of the cotyledons. Similar results were obtained for corn by Chung and Pfost (1967). The EMC and the heat of desorption were also different for each component (starch, hull, gluten and gum) of the kernel.

The fact that the pericarp has different hygroscopic properties from the other kernel components is another indication that it might have an important effect on the drying behavior of shelled corn. Especially since the pericarp is the portion of the kernel that is directly exposed to the drying air. It seems logical that the surface moisture content of the kernel during drying is related more to the EMC of the pericarp than to the average EMC of the shelled kernel. This could explain why the value of the surface moisture content or dynamic EMC, obtained empirically to give the best fit of experimental data, is always higher than the EMC obtained by the static method for the whole kernel.

The effect of the pericarp characteristics on the drying rate of corn was discussed theoretically by Chu (1966). He pointed out that if the resistance to moisture transfer is mainly in the pericarp of the kernel then the logarithmic equation applies:

$$MR = e^{-kt} = e^{-(SVR)\,(1/PER)\,Dt}$$

where SVR is the kernel surface-to-volume ratio, PER the pericarp thickness

and D the diffusion coefficient of the pericarp. This equation indicates that the drying time is inversely proportional to the kernel surface-to-volume ratio (SVR) and (1/PER).

On the other hand, if the resistance to moisture transfer is uniformly distributed within the kernel, the diffusion equation applies. The solution of the diffusion equation for a sphere, an infinite plane and an infinite cylinder with a constant and uniform diffusion coefficient is given by Brooker et al. (1974). In all cases, the drying time was inversely proportional to the square of the kernel surface-to-volume ratio. Van Rest (1949) (cited by Chu, 1966) found that for kernels of corn ground to one third of the normal size the drying rate was nine times higher which verifies that the drying time is inversely proportional to the square of the kernel surface-to-volume ratio. This result suggests that the drying resistance is not concentrated at the kernel surface in the pericarp. It does not necessarily mean, however, that the pericarp has no effect on the drying rate or that the drying resistance is uniformly distributed.

5.2.3 THIN-LAYER DRYING RATE DIFFERENCES AMONG CORN STRAINS

Varietal differences in thin-layer drying rate among corn strains have been studied by Stroshine et al. (1981). In their study the drying rate of 4 inbreds, 4 single cross hybrids, and 5 commercial hybrids were compared. The drying rate was expressed as the time required to reduce the moisture content from 25 to 15% (w.b.) at 93.3°C. Each test was replicated three times and significant differences in drying rates were found. The average drying time for the fastest and slowest drying hybrids were 31.0 and 39.6 minutes, respectively. This represents approximately a 25% difference in drying time between the two hybrids. The coefficient of variation for

replicates was only 1.0% and 5.5% for the slowest and fastest drying hybrid, respectively. As part of their study various quality parameters of the hybrids were compared, including the thousand kernel weight (TKW) on a dry basis. The TKW was found to vary from 170 to 340 g for the corn inbreds/hybrids tested. Such large differences might partially explain drying rate differences, since the TKW is directly affected by the density and volume of kernels. As discussed earlier these two physical properties might affect the drying rate. Although both the drying rate and the TKW were measured for each corn inbred/hybrid tested, no attempt was made to determine if both quality parameters were correlated.

Levesque et al. (1986) compared the thin-layer drying behavior of 29 corn inbreds/hybrids. During 1984, drying tests for 5 hybrids were performed at 40, 50 and 60 °C. The other corn strains were tested at 50 °C the following year. All the tests were done at a constant dew-point temperature of 27.5 °C and constant air velocity of 0.5 m/s. The drying rate was expressed in terms of the time to dry the samples from an initial moisture content (MC) of 40% (d.b.) to a final MC of 18.3% (d.b.) which is representative of the range of moisture removal during actual drying operations in Ontario. The kernel density, surface-to-volume ratio and pericarp thickness were measured for each corn strain tested and were correlated with the drying rate. An overall drying equation was obtained to predict the drying behavior of corn at 50 °C and 30% R.H. from the kernel physical properties associated with the drying rate.

The drying rate was found to be significantly correlated with the pericarp thickness and the kernel surface-to-volume ratio. It was estimated that the drying time increased by 16.7% with an increased in pericarp thickness over the range from 0.066 to 0.114 mm and decreased by

5.5% with an increase in surface-to-volume ratio over the range from 1.004 to 1.190 mm^{-1}. The drying time was not found to be significantly correlated with the kernel density over the range from 1.01 to 1.15 x 10^{-3} g/mm^3.

If it were possible to identify those specific anatomical, physiological and compositional characteristics which give desirable quality traits, such as higher drying rates, corn breeders could select for these characteristics in the development of new hybrids. For this to be successful, it is necessary, however, that the factors affecting the drying rate be hereditary. The inheritance of the factors affecting field drying rate has been studied by Pury and Crane (1967a). The field drying rate was simulated by drying husked ears in a forced-air dryer for 18 hours at 38°C. They found that the factors affecting drying rate were indeed inherited. Similarly, the inheritance of pericarp thickness was studied by Ho et al. (1975). They concluded that selection for pericarp thickness should be effective and relatively rapid.

5.2.4 SUMMARY

1. Research on the field drying rate of corn has shown that the rate differs for various corn strains and that it depends on the ear size and weight, and the pericarp thickness of the kernel.
2. Difference is the drying rate of different strains of shelled corn has also been reported.
3. The resistance to artificial drying of shelled corn has also been described to the pericarp thickness, while the rate was said to be proportional to the surface-to-volume ratio of the kernel.
4. Since the equilibrium moisture content of the chemical constituents of the kernel varies, the drying rate of different strains will also be

influenced by the relative chemical composition of the strains.

5. It appears desirable to consider the field and artificial drying characteristics of the pericarp and other parts of the kernel in the development of new corn strains.

6. It is not entirely clear whether the pericarp thickness is important or the lack of pericarp and the degree of kernel damage (see 5.3.1)].

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5.3 MECHANICAL CONDITIONING

5.3.1. EXPERIMENTAL WORK

Researchers at the Hungarian Institute for Techniques of the Ministry of Food and Agriculture postulated that the resistance of the pericarp to moisture transfer during drying requires energy input which becomes unavailable for moisture evaporation (Anon, 1973). This was considered to be one of the reasons why the specific energy consumed by most modern, efficient grain dryers is 1.5 to 2 times the theoretical energy required. In order to minimize the effect of the pericarp, they developed an apparatus which punctured the pericarp with a series of needles. In an experimental verification of the process, thin-layer drying experiments were performed in a desiccation chamber using 20 samples of 20 grams each of the treated (punctured) and untreated kernels. All the samples of treated and untreated kernels were dried in the same chamber at the same time to assure uniformity in the drying conditions. Each test was replicated three times for each drying condition. It was reported that the drying rate increased with puncture depth over the range of 2 to 2.5 mm, and with the number of holes punctured over the range of 2 to 6 per kernel. It was also found that the effect of punched holes on the drying rate increased with drying temperature ranging from 70 to 130 ^{o}C and initial moisture content ranging from 20 to 35 percent.

The results of the thin-layer experiments were verified by performing drying tests in a deep bed of 150 mm. To obtain identical drying conditions, the treated and untreated corn was placed in a tray with a perforated bottom and separated by a vertical metal partition. The drying air was blown through the grain bed at a velosity of 0.65 m/s and a temperature of 110 ^{o}C.

The initial moisture content was 30% for both the treated and untreated kernels. They found that 28.5% less time was required to dry the treated kernels to a final moisture content of 14% compared with the untreated ones. Since heat was applied at the same rate, the energy spent to dry the punctured corn was 40% less as well.

When it appeared that the pericarp had indeed an effect on the moisture flow, it was postulated that the moisture flow should vary according to the variation in pericarp thickness at different locations on the kernel. To verify this hypothesis, untreated corn was dried by immersion in paraffin oil. As the oil was gradually heated to 110 ^{o}C, steam bubbles were observed to leave the kernels only at the thin extremety containing the germ. Upon examination of kernels it was discovered that a small area of the pericarp was missing at the germ end. This part of the pericarp remained on the cob even if the shelling was done by hand. Similar experiments with treated corn showed steam bubbles leaving the kernels at the puncture sites as well.

Similar experiments with combined corn and hand-shelled corn by Otten (1986) have shown that many combined kernels have received enough damage to allow escape of steam at sites other than the tip cap. However, carefully hand-shelled corn showed moisture flow only at the tip cap. Therefore the drying rate of shelled corn may be related not to the pericarp thickness but to the amount of pericarp left on the cob and the level of kernel damage caused by harvesting and handling. It is however possible that different strains may exhibit a difference in damage susceptibility and pericarp adherence to the cob. In any case, the observations do point out that it would be incorrect to use the work done will earn corn in determining field drying rates and apply the results to artificial drying of shelled corn.

As a result of the laboratory studies the Hungarian Institute obtained patents for the United States and the Soviet Union. In addition, after a delay of some 10 years, a 15 t/h machine was constructed for on-farm testing of the puncturing process and its effect on the storability of the treated grain (Ember et al., 1983). Corn with an initial moisture content of 22 to 25% was treated and dried to 11 to 13% in 1982. The equipment worked satisfactorily; however, the energy savings varied from only 1.2 to 12.5%. This was considerably lower than the 40% savings obtained in the laboratory and may perhaps be due to a difference in damage levels of the untreated corn. The report does not indicate whether the samples used in the laboratory were hand or combine shelled.

Both treated and untreated corn was placed in storage to a depth of 2 m or less. Corn samples were collected monthly and quality determinations showed that there was no significant difference between the treated and untreated corn after 5 months of storage.

5.3.2. SUMMARY

1. Artificially induced punctures resulted in an increased drying rate and reduced energy consumption (40%) in laboratory experiments.
2. The difference between treated and untreated corn decreased significantly during field trials with combined corn.
3. Visual observations of untreated corn dried in a paraffin oil bath showed steam to leave only at the tip cap of the kernels. In the case of damaged and punctured kernels, steam left at the sites of injury.

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